RECENT RESULTS FROM MINOS AND FUTURE PROSPECTS

Jonathan M. Paley for the MINOS Collaboration
Indiana University

Fermilab Users' Meeting
June 5, 2008

The MINOS Collaboration

Argonne - Arkansas Tech - Athens - Benedictine - Brookhaven - Caltech - Cambridge - Campinas - Fermilab - Harvard - IIT - Indiana - Minnesota-Twin Cities - Minnesota-Duluth - Oxford - Pittsburgh - Rutherford - São Paulo - South Carolina - Stanford - Sussex - Texam A&M - Texas-Austin - Tufts - UCL - Warsaw - William & Mary

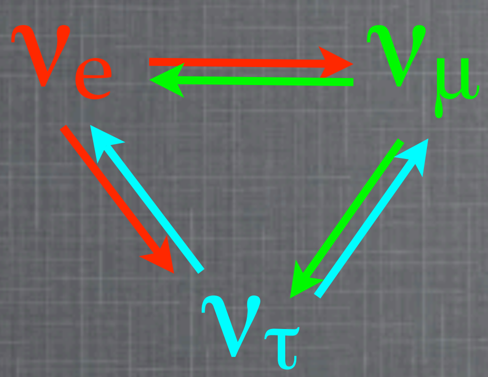
2007-08: Very Productive Year!

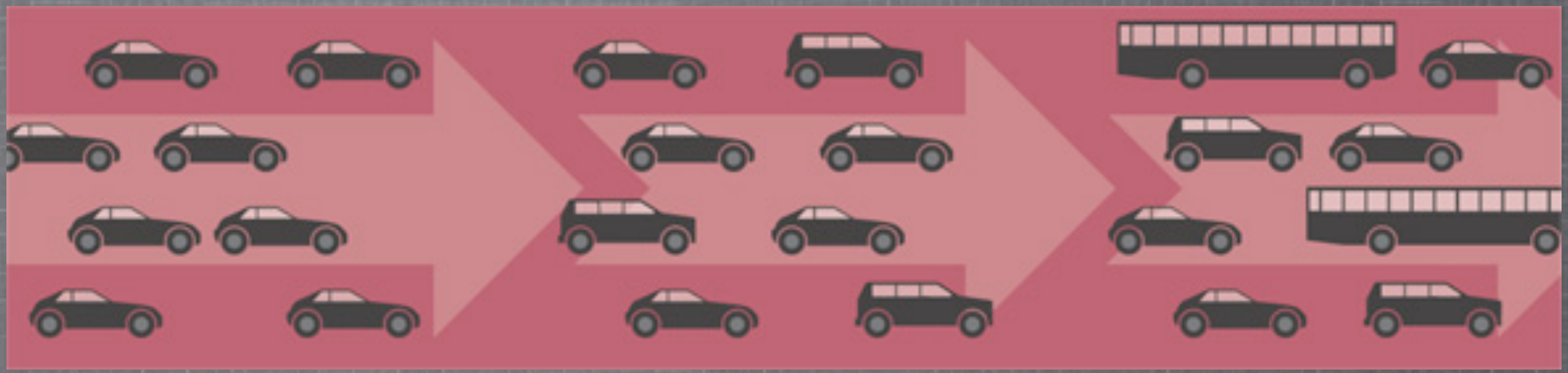
- 4 articles published or submitted to peer-reviewed journals
- 6 theses
- 2 boxes opened
- significant progress in understanding backgrounds and systematic uncertainties in all analyses

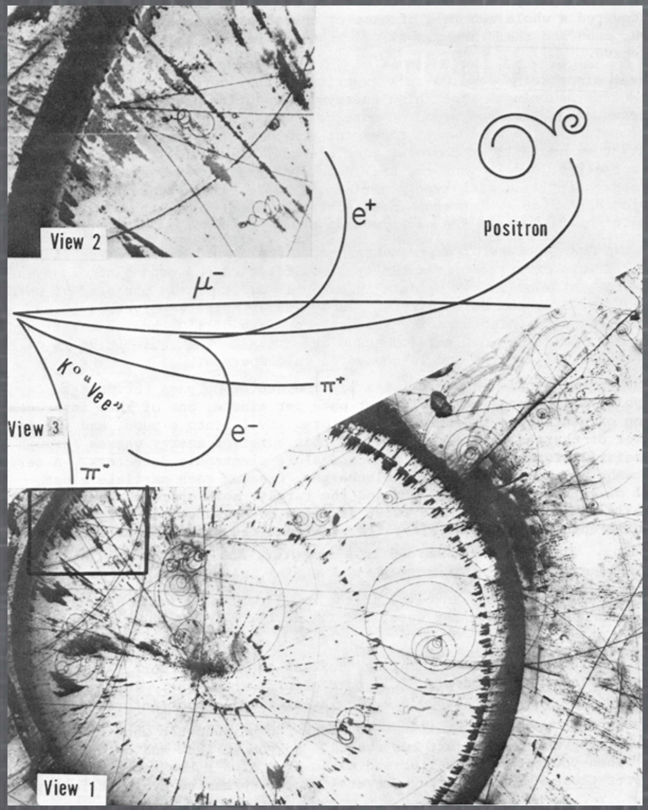
Outline of the Rest of this Talk

- The MINOS Experiment
  - Goals
  - Detectors
- What's new (2007-08)
  - ν_μ CC Analysis
  - NC Analysis
  - Other analyses completed this year
- Future Prospects
  - ν_e Analysis
  - Other ND ν interactions

Goals of the MINOS Experiment





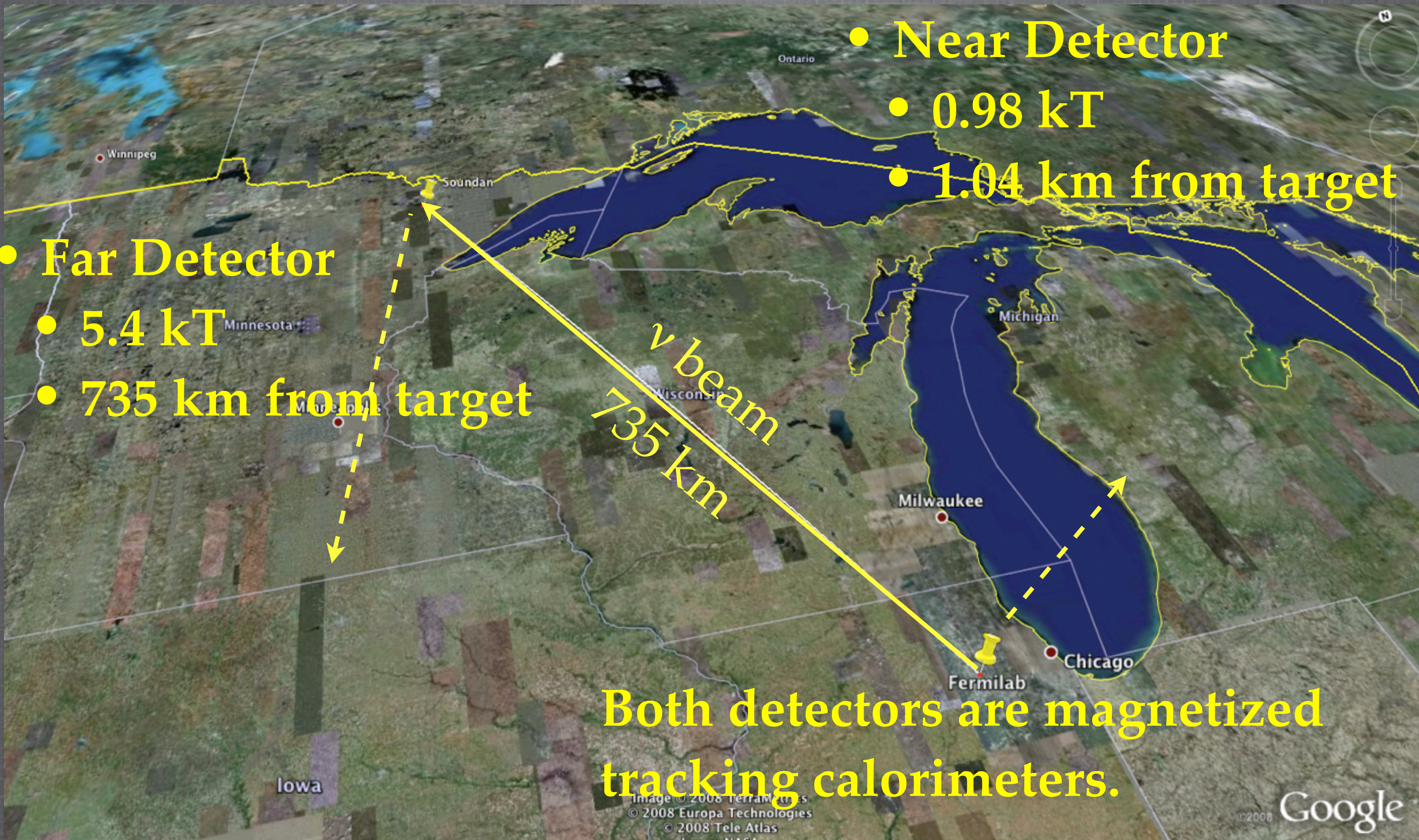


- Make precise measurement of Δm^2 and $\sin^2(2\theta)$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\,\sin^2(1.27\,\Delta m^2\,L/E)$$

- Confirm oscillations vs. other explanations (decay, decoherence)
- Search for subdominant $\nu_\mu \to \nu_e$
- CPT tests
- Search for sterile neutrinos
- Atmospheric neutrino and cosmic ray

The MINOS Experiment



- Near Detector
  - 0.98 kT
  - 1.04 km from target
- Far Detector
  - 5.4 kT
  - 735 km from target

Both detectors are magnetized tracking calorimeters.

The MINOS Experiment

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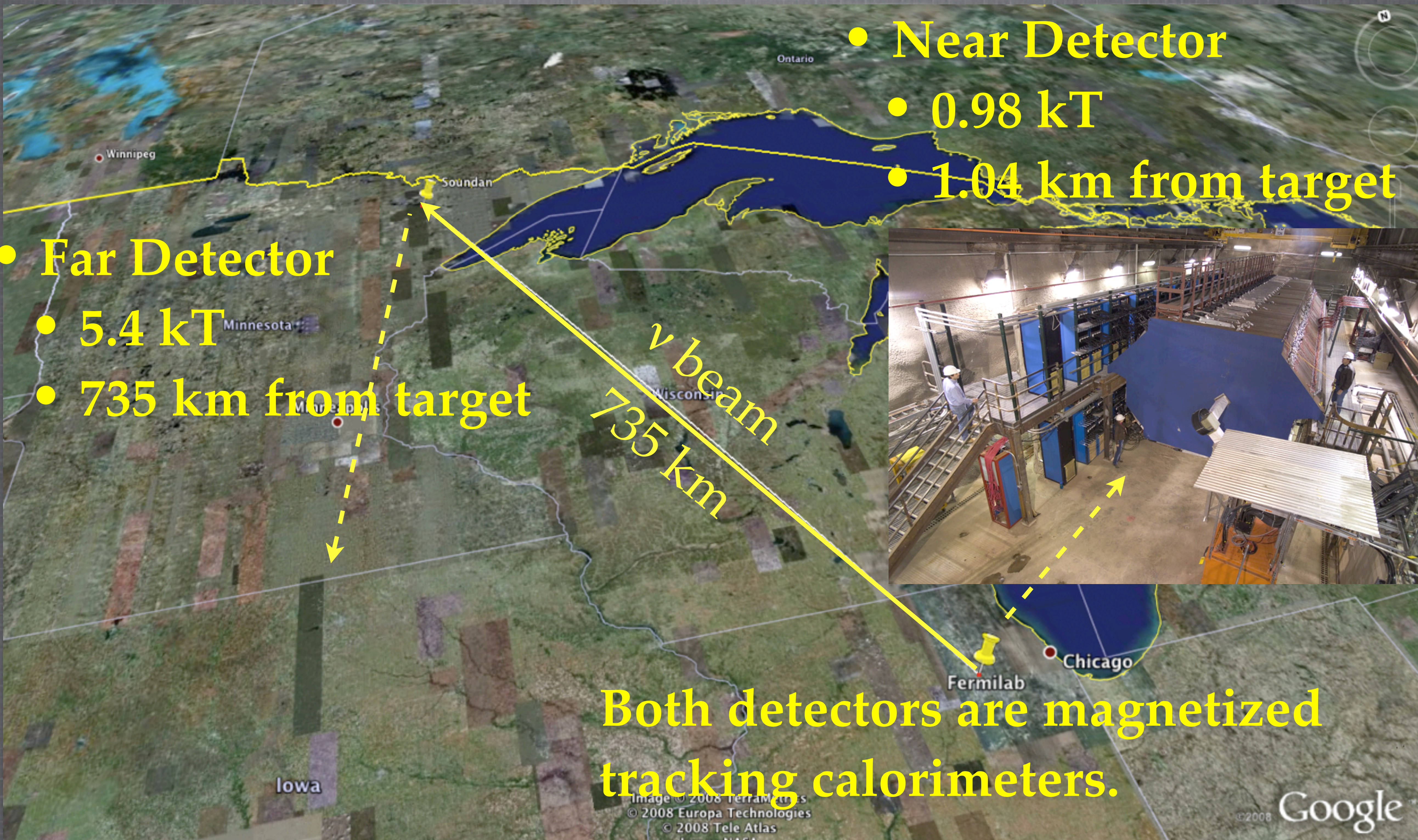

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The MINOS Experiment

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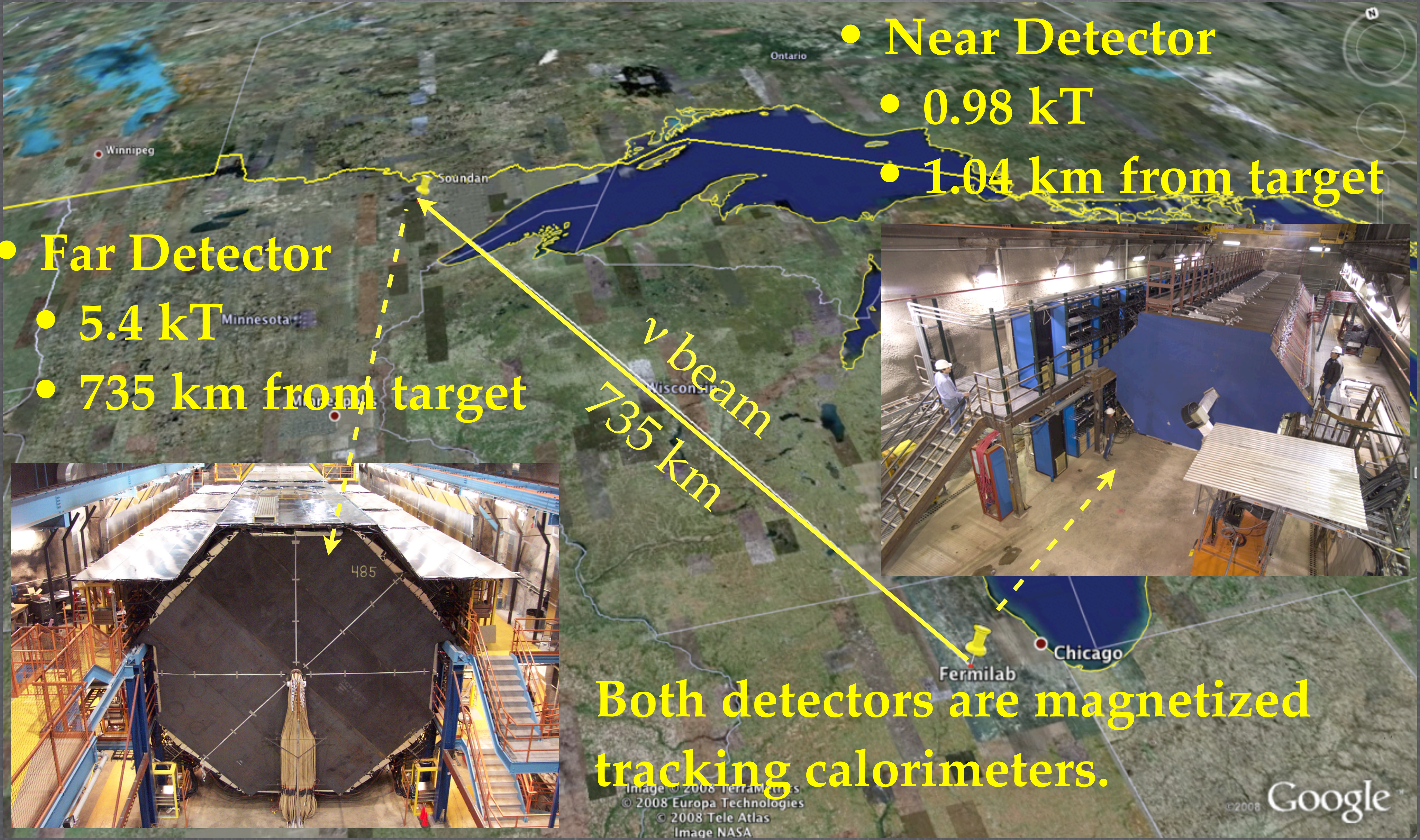
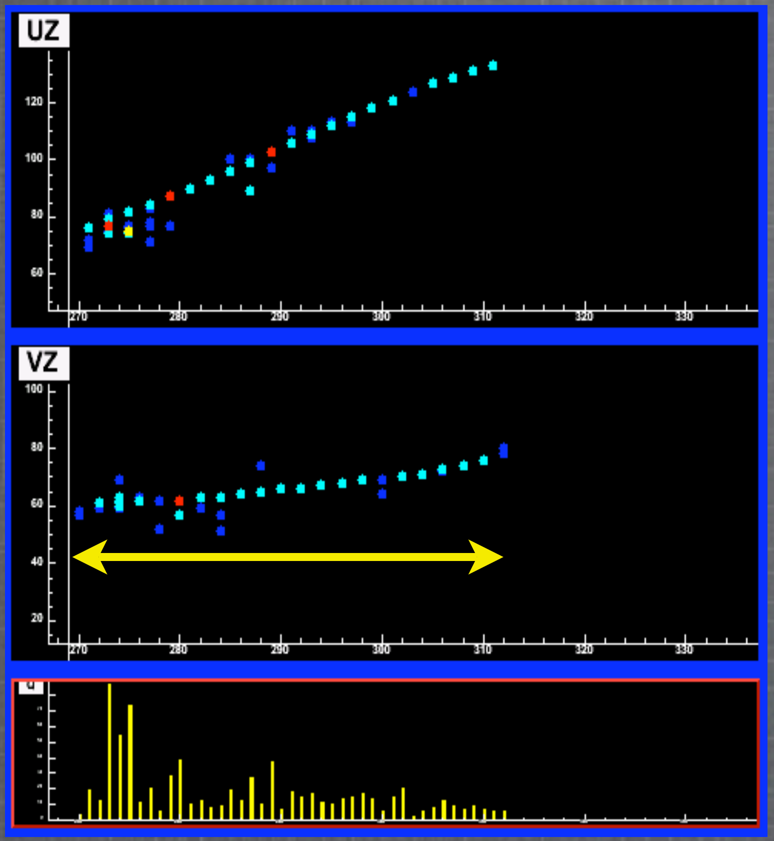


Both detectors are magnetized tracking calorimeters.

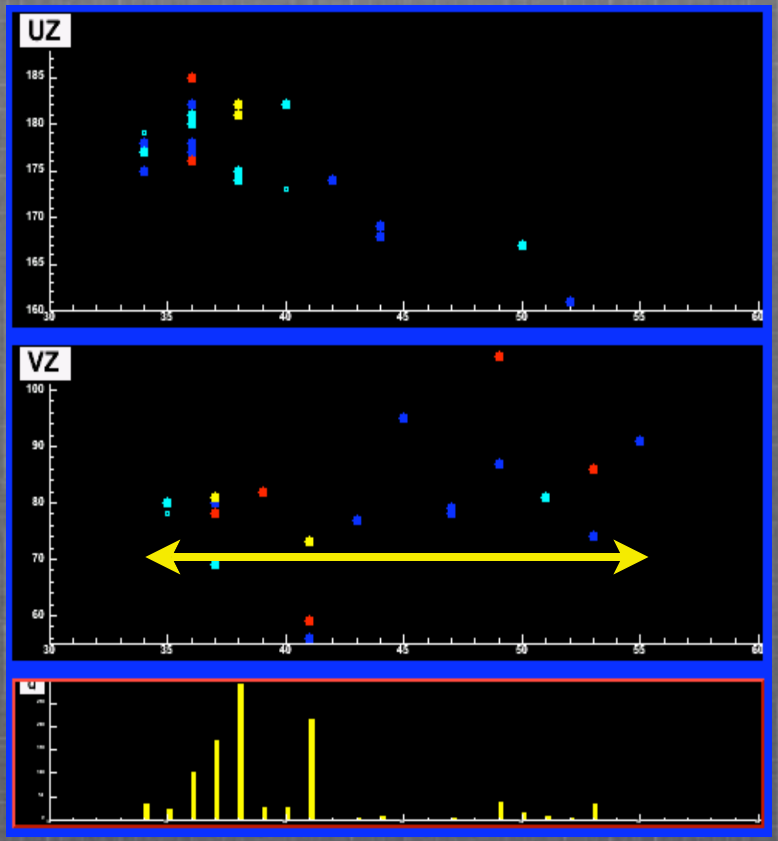
Identifying Events in MINOS

ν_μ CC event



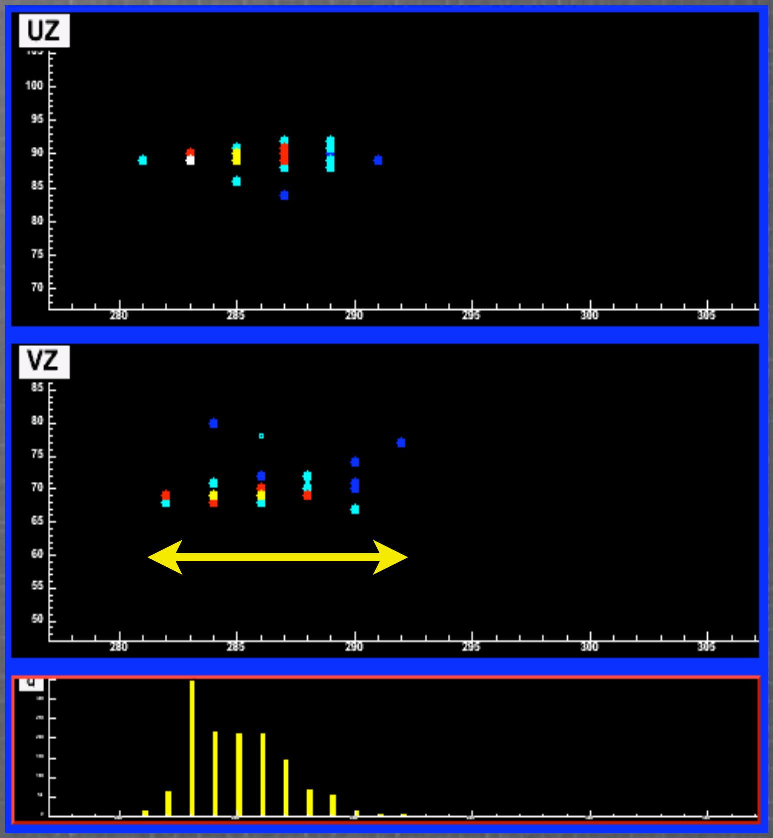
Long μ track +
shower at vertex

NC event



Short, diffuse event.

ν_e CC event

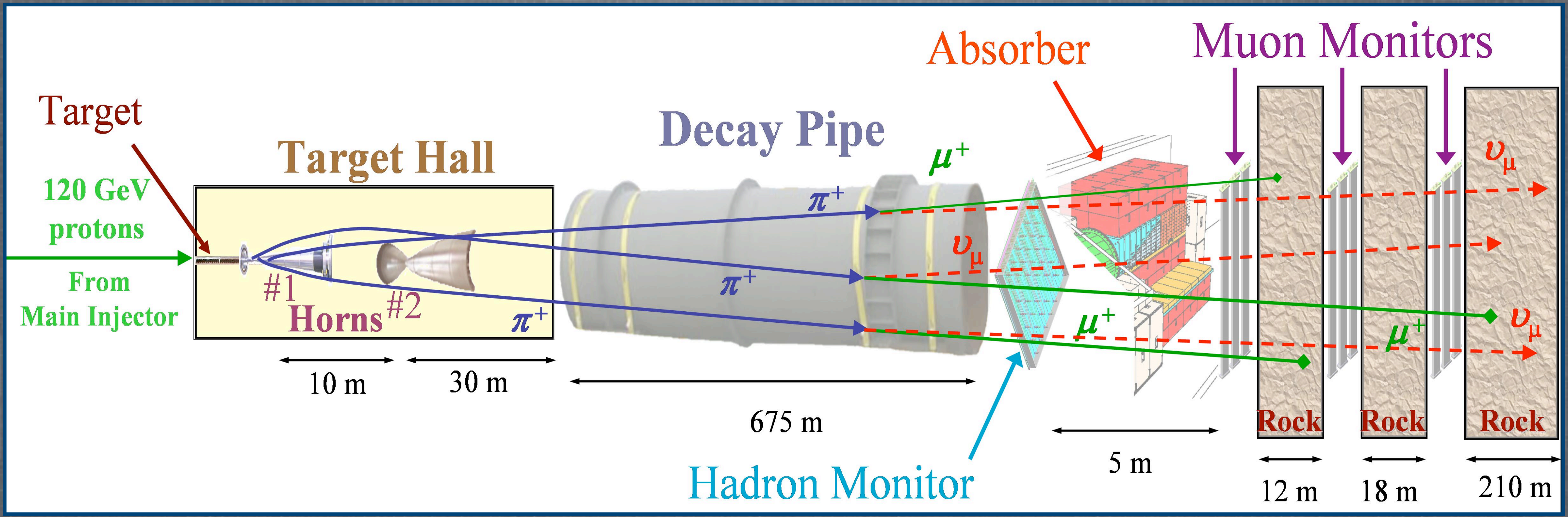


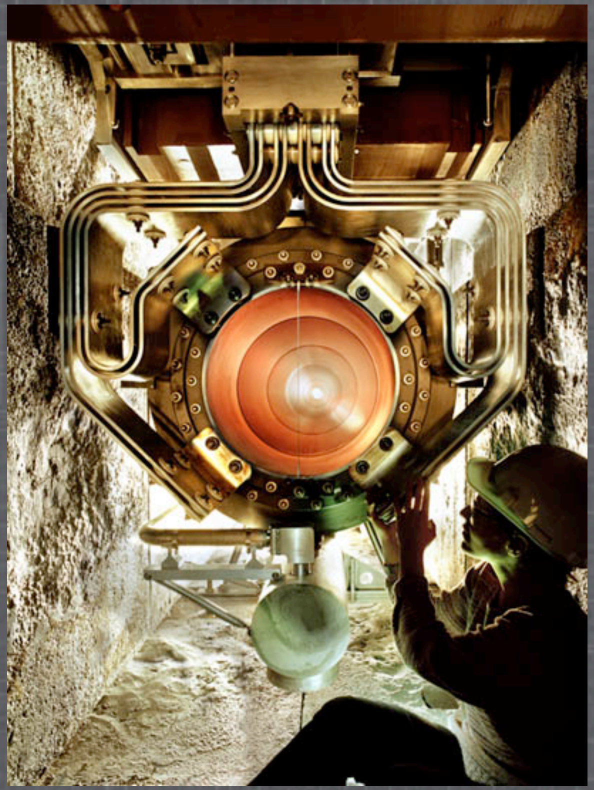
Short event with
EM shower profile.

$$E_\nu = E_{shower} + E_\mu$$

$\delta E_{shower} = 55\%/\sqrt{E}$ $\delta E_\mu = 6\%$ range, 10% curvature

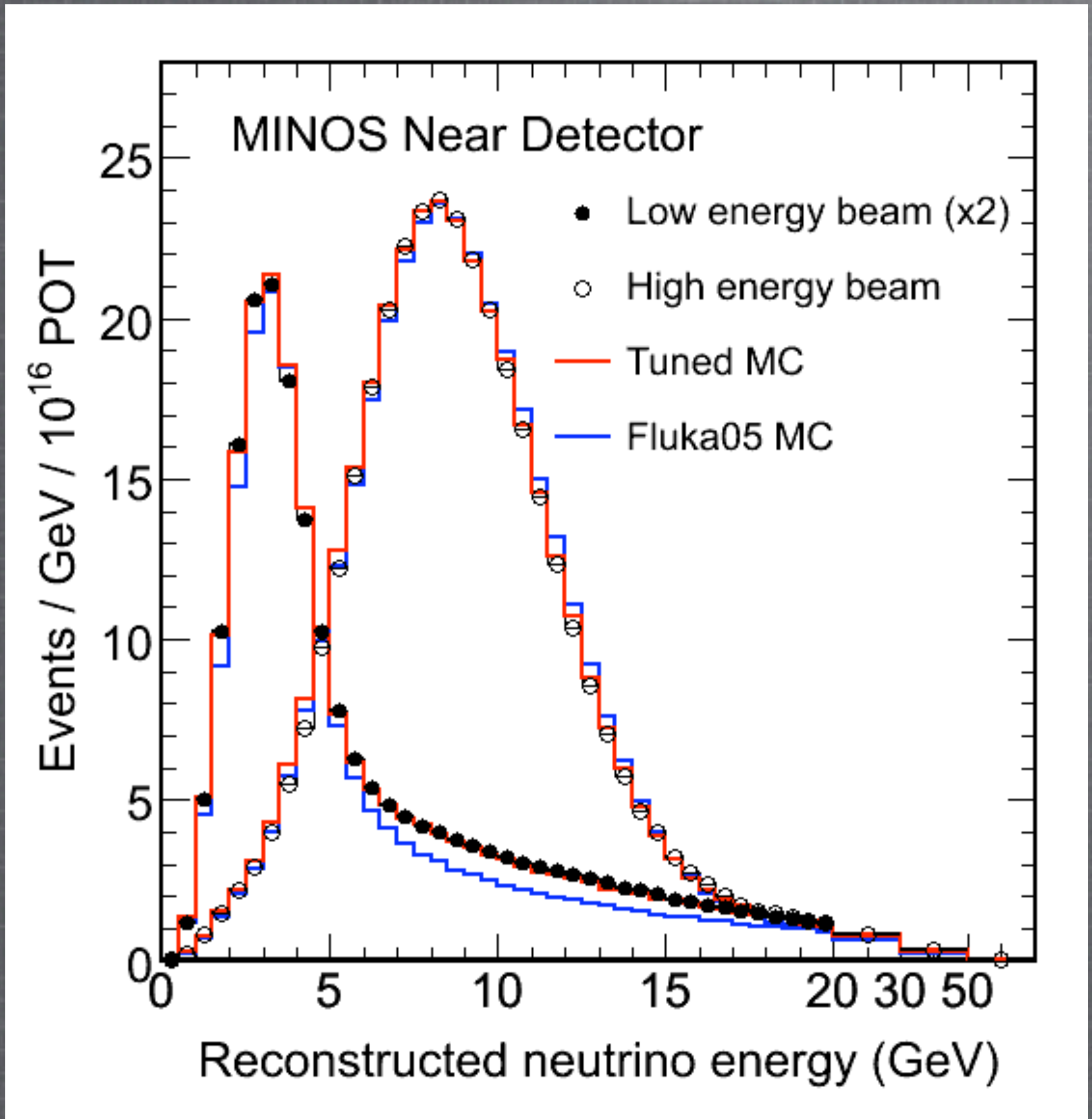
Producing Neutrinos at the Main Injector

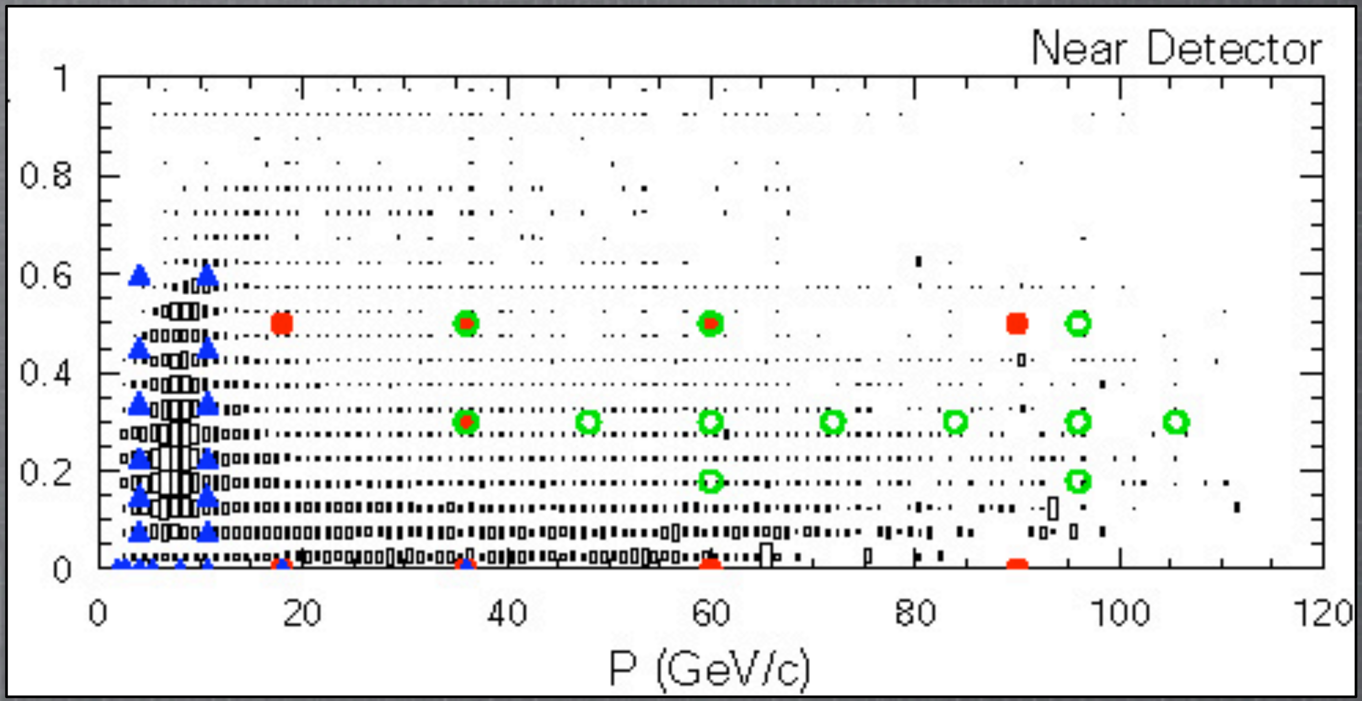




- **Mesons produced in 120 GeV/c p + 165% λ_L graphite target interactions are focused in two magnetic horns.**
- **ν beam energy is *tunable* by moving target position longitudinally w.r.t. the horn positions.**
- **In LE beam configuration, beam is composed of 92.9% ν_μ, 5.8% $\overline{\nu}_\mu$, and 1.3% ν_e and $\overline{\nu}_e$.**

Predicting the Flux

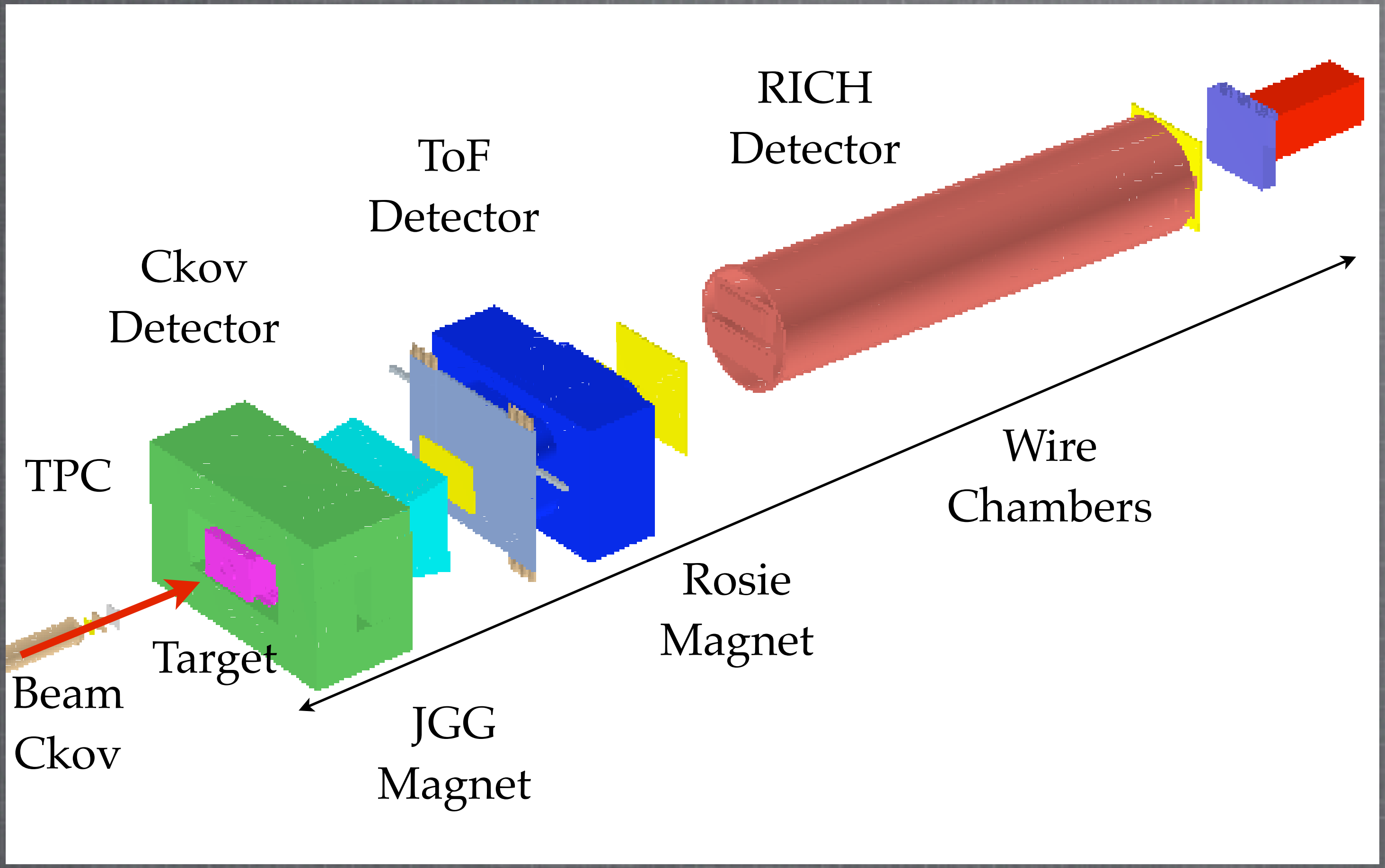


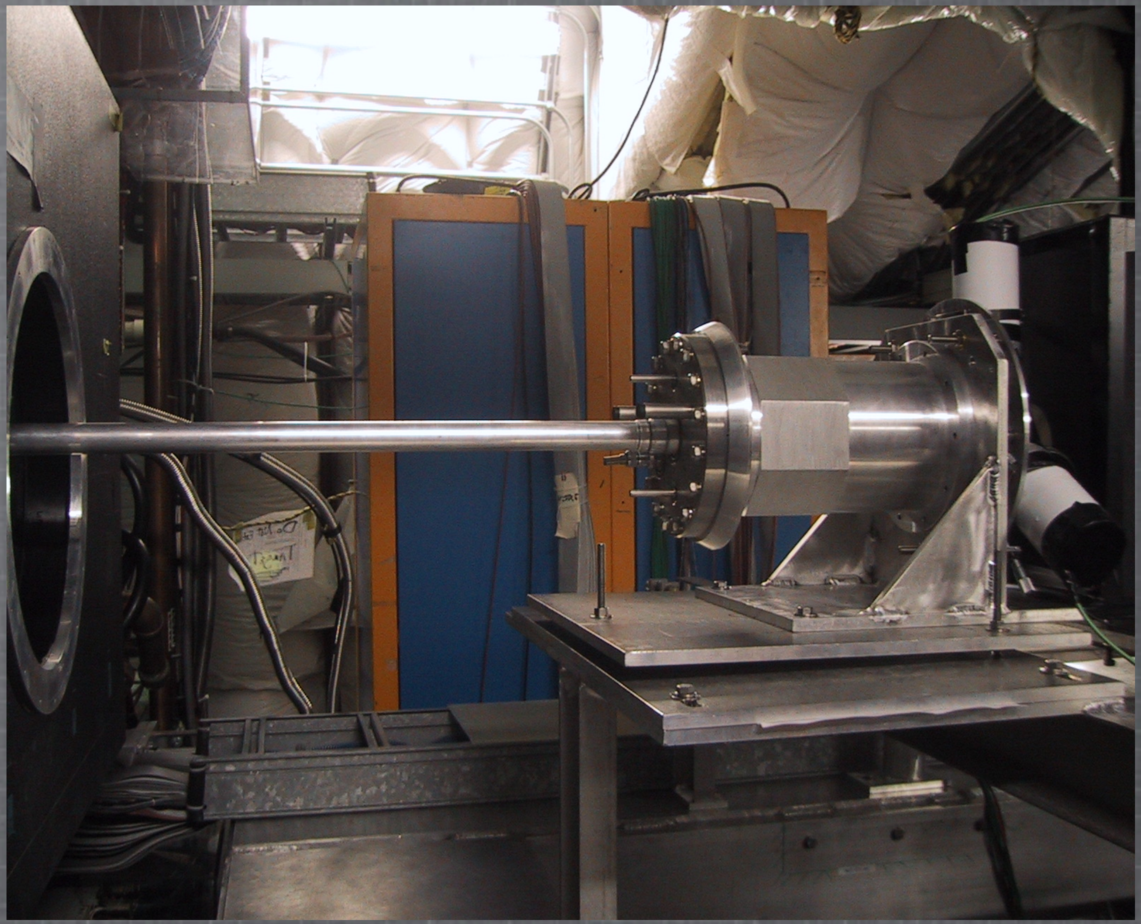


- MINOS uses Fluka06 MC to predict the ν flux.
- Uncertainty on flux is ~30% due to lack of hadron production data.

- To improve our data-to-MC agreement, we tune the Fluka MC to ND energy spectra of different beam configurations.
- These beam-reweighted spectra are used in all analyses discussed today.

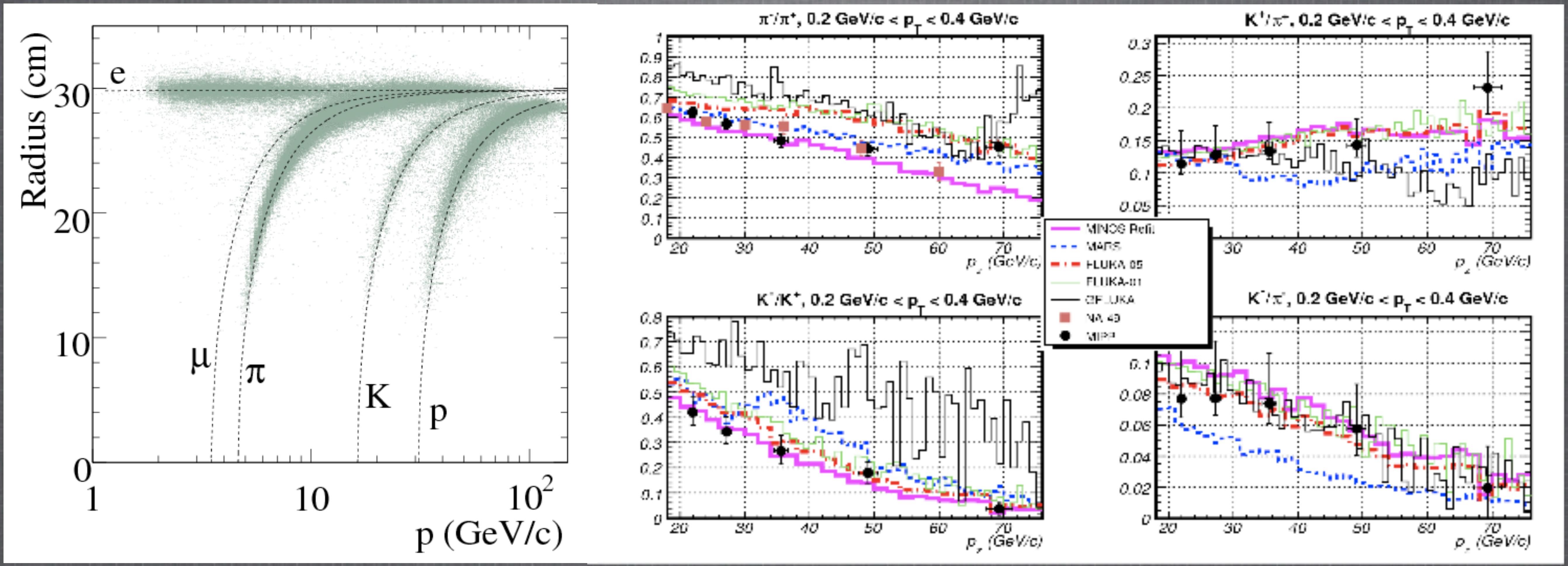
Measurement of Hadron Production off NuMI Target in MIPP





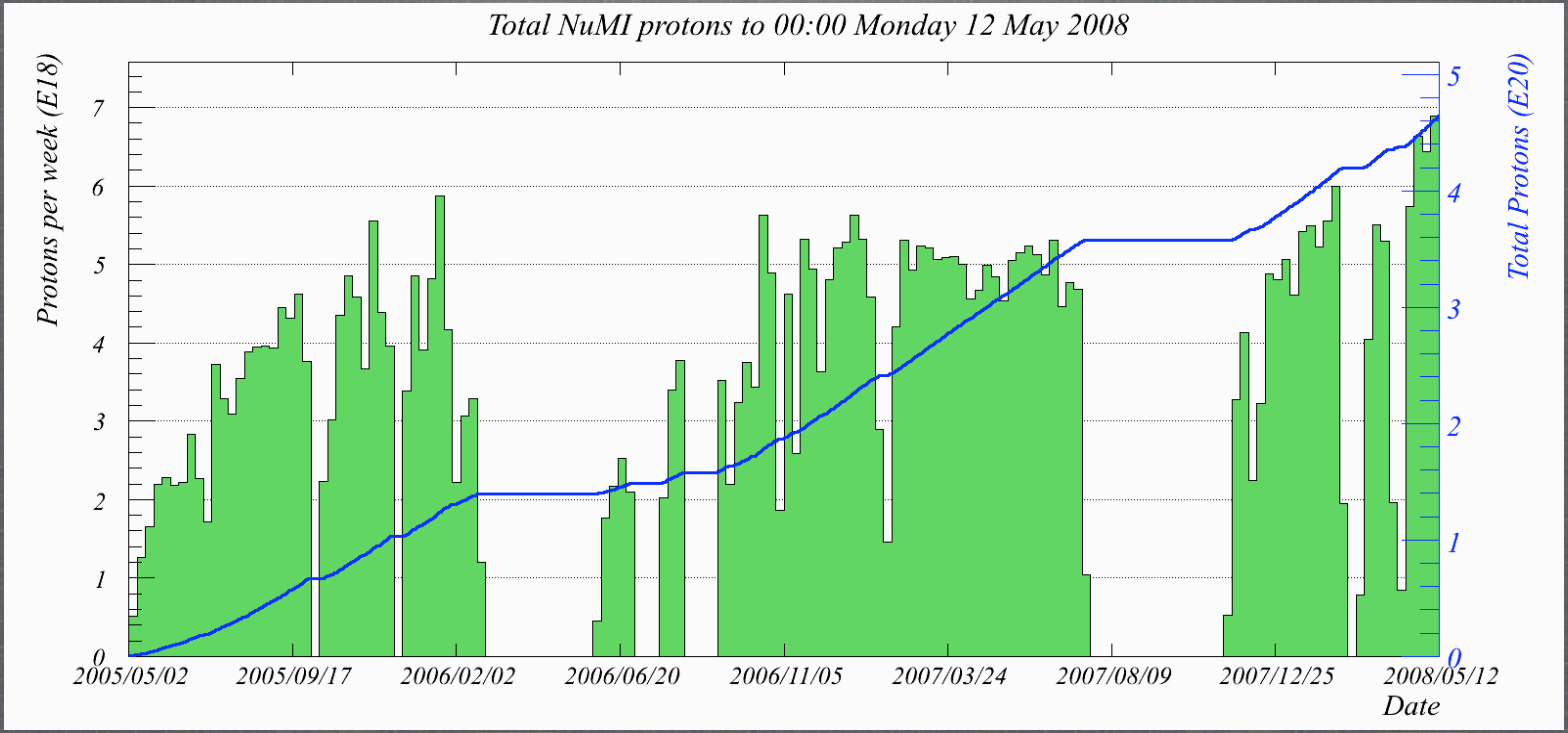
- Main Injector Particle Production (MIPP) is a fixed target experiment with beams of π, K and p from 5-120 GeV/c and LH2, C, Be, Bi, U targets.
- MIPP has collected 1.6×10^6 events of 120 GeV p striking the MINOS target.

Status of MIPP Analysis



- π^-/π^+, K^-/K^+ , and K/π production ratios above 20 GeV/c agree well with expectations from MINOS beam-tuning.
- The MIPP Collaboration has completed the calibration of all PID detectors and is now focusing on the hadron production measurement from the NuMI target data set.
- See poster by Yusuf Gunaydin.

NuMI Beam

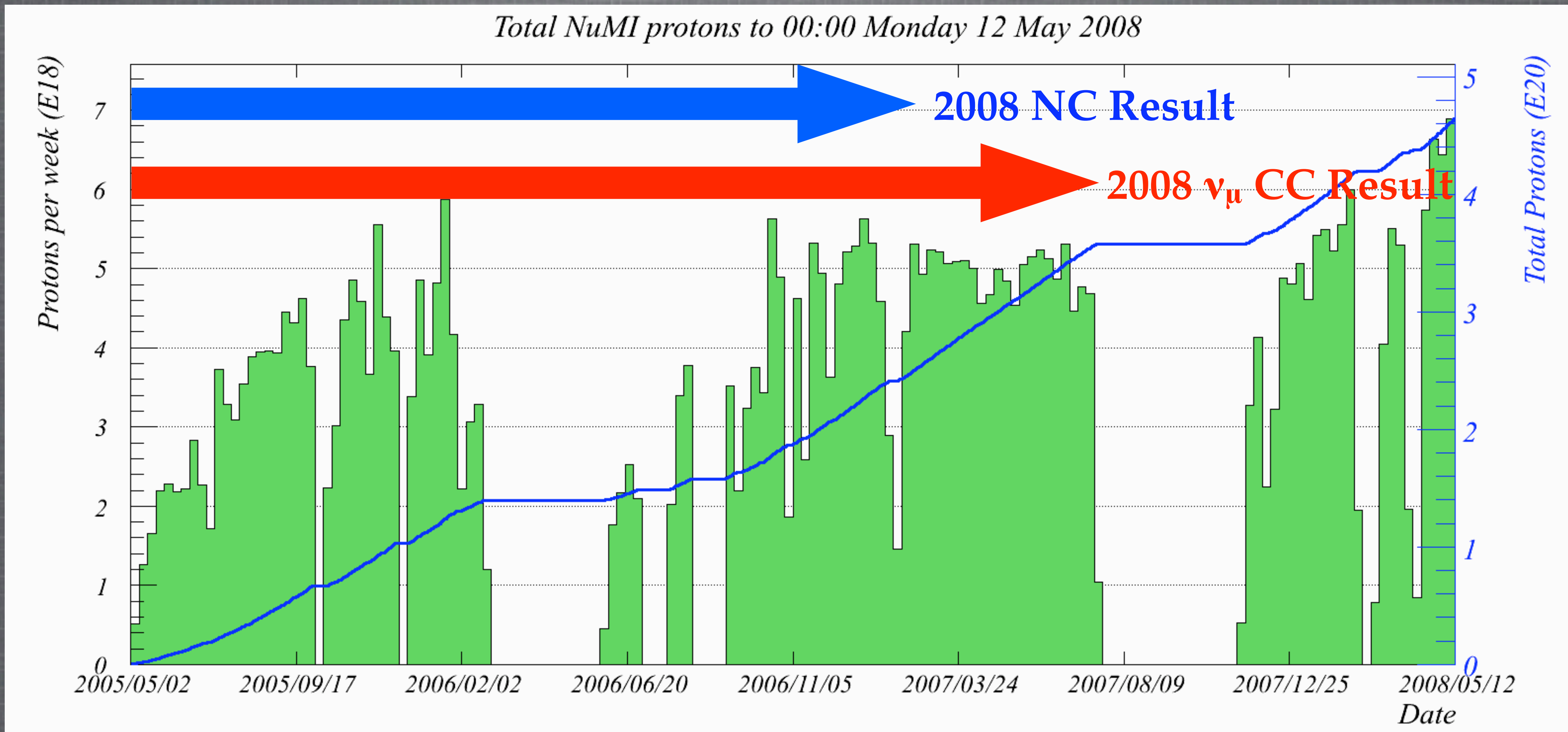


Run I

1.27 x 10^{20} POT

2006 ν_μ CC Publication

NuMI Beam

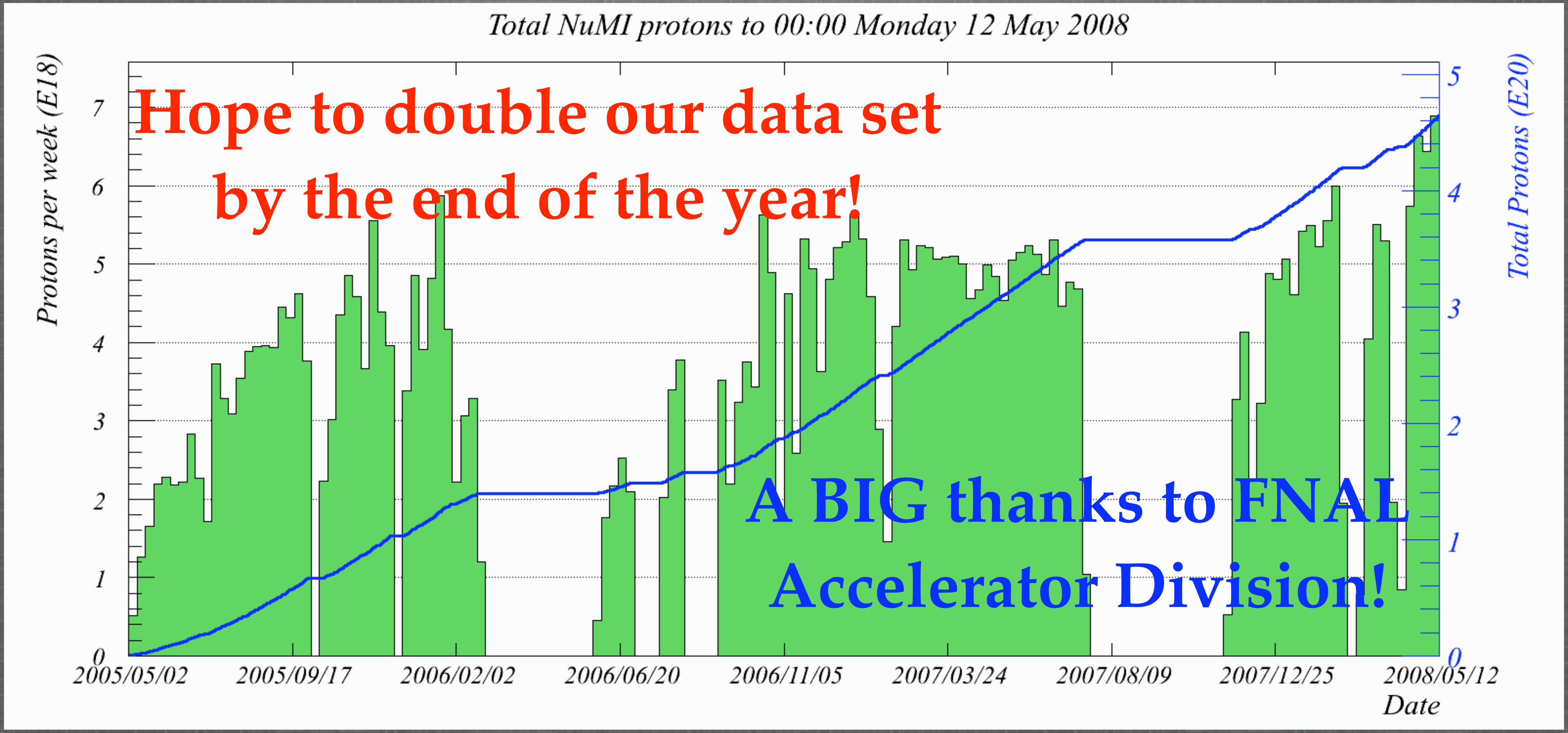


Run I
1.27 x 10^{20} POT

Run II
1.94 x 10^{20} POT

HE beam:
0.15 x 10^{20} POT

NuMI Beam



Run I
1.27×10^{20} POT

Run II
1.94×10^{20} POT

Run III
1.1×10^{20} POT

HE beam:
0.15×10^{20} POT

ν_μ CC Analysis

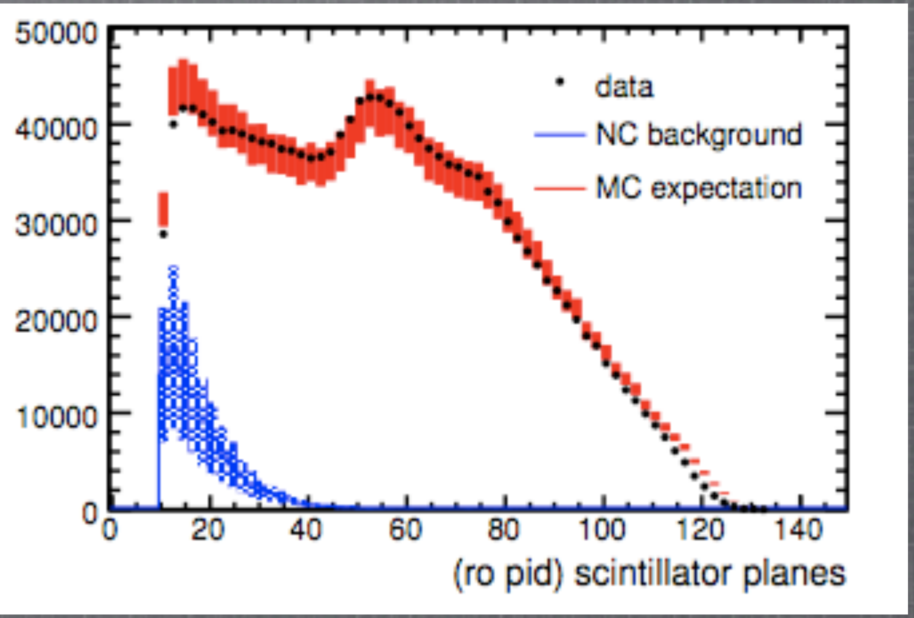
Precision measurement of
Δm^2 and $\sin^2(2\theta)$

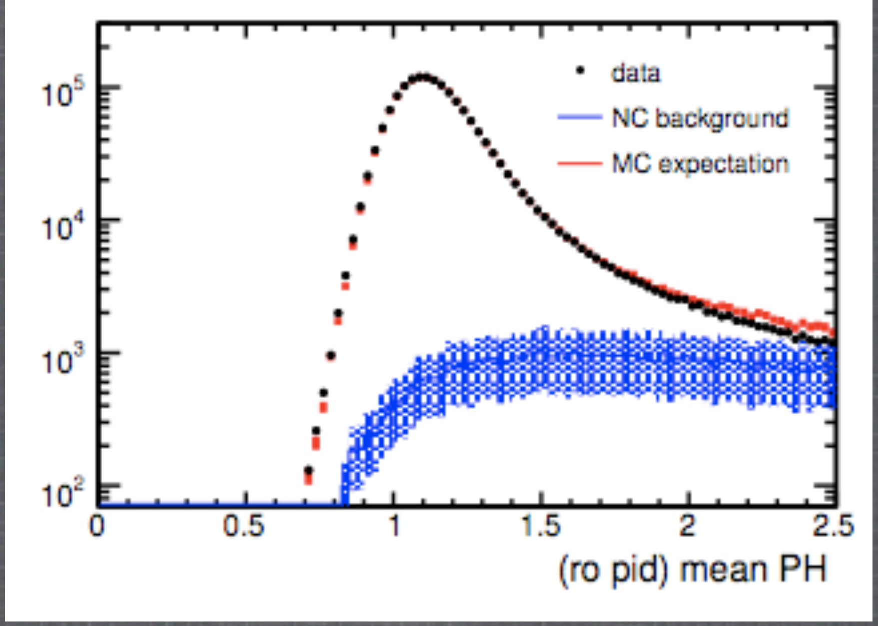
ν_μ CC Event Selection

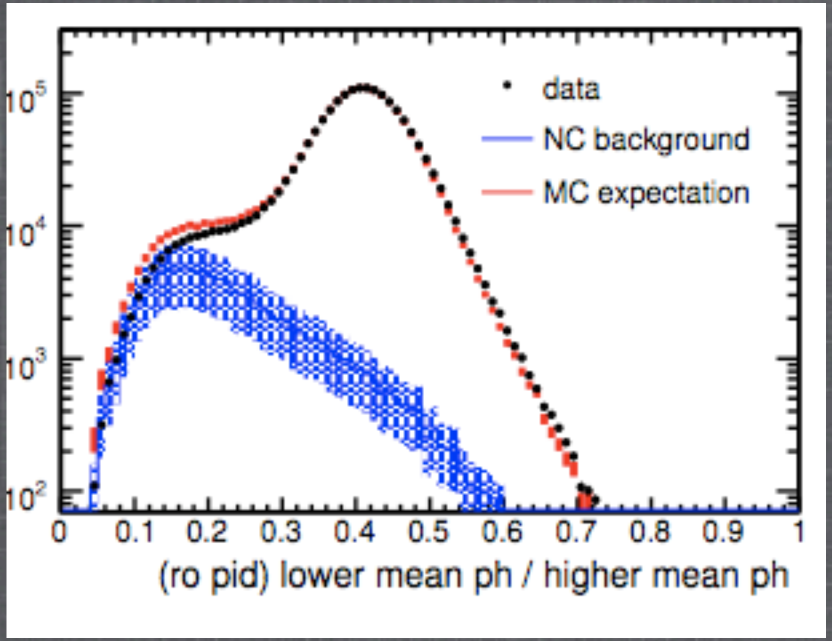
- Events must have:
  - at least 1 reconstructed track
  - event vertex must fall within fiducial volume
  - track must be negative charge (no $\bar{\nu}_\mu$)

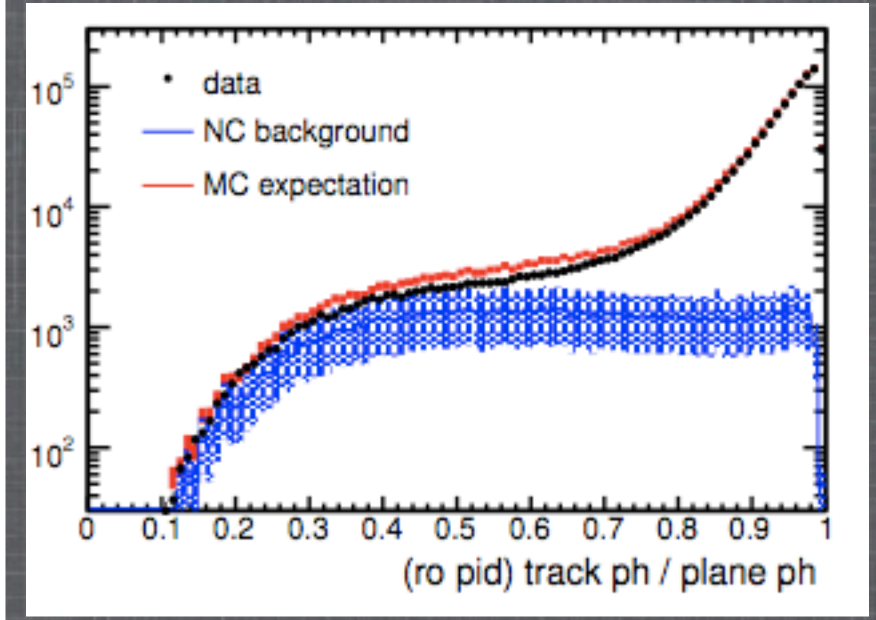
ν_μ CC/NC Separation

- CC/NC separation achieved via a kNN event selection based on:
  - Track length
  - Mean pulse height
  - Fluctuation in pulse height
  - Transverse track profile

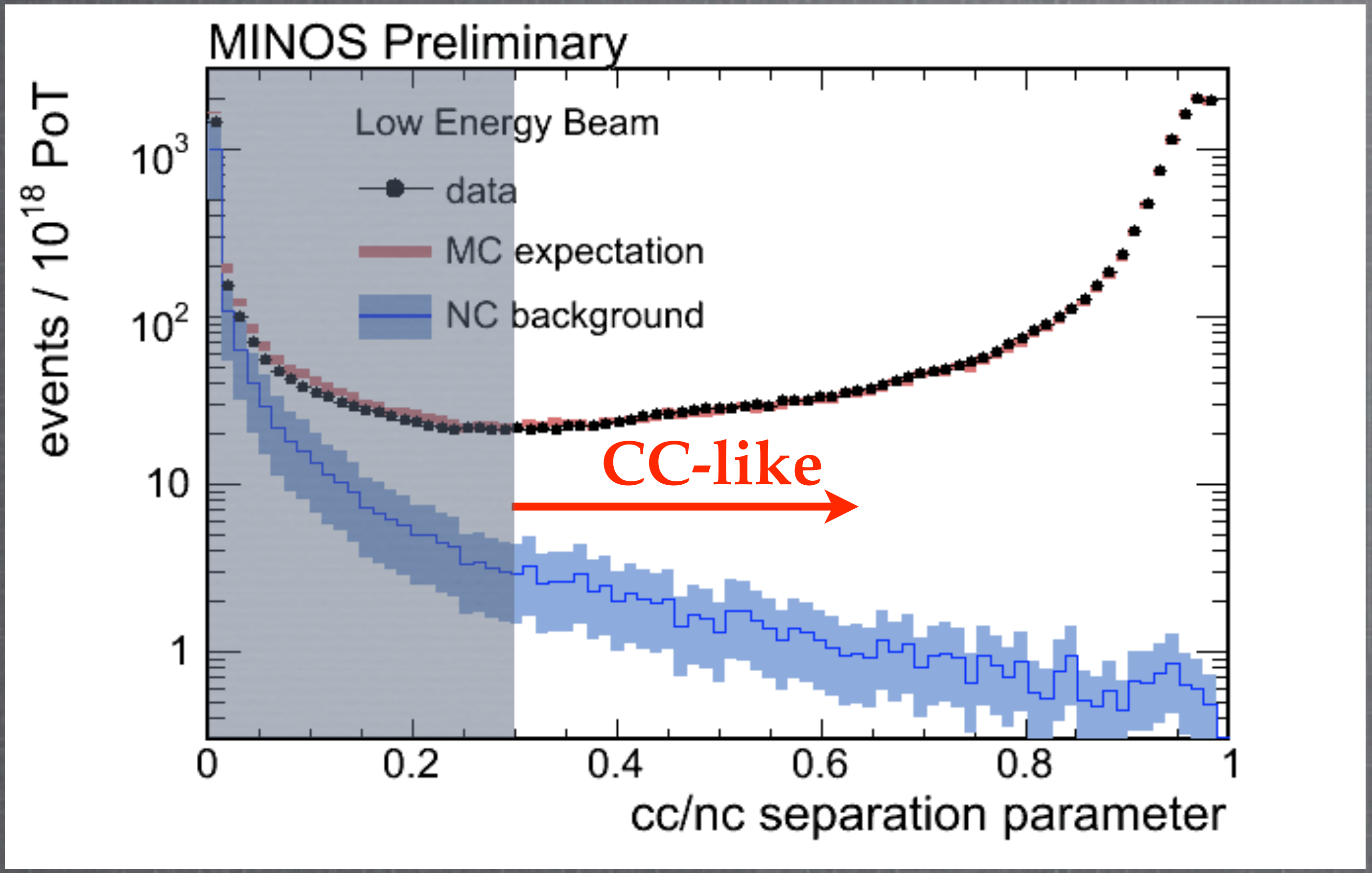


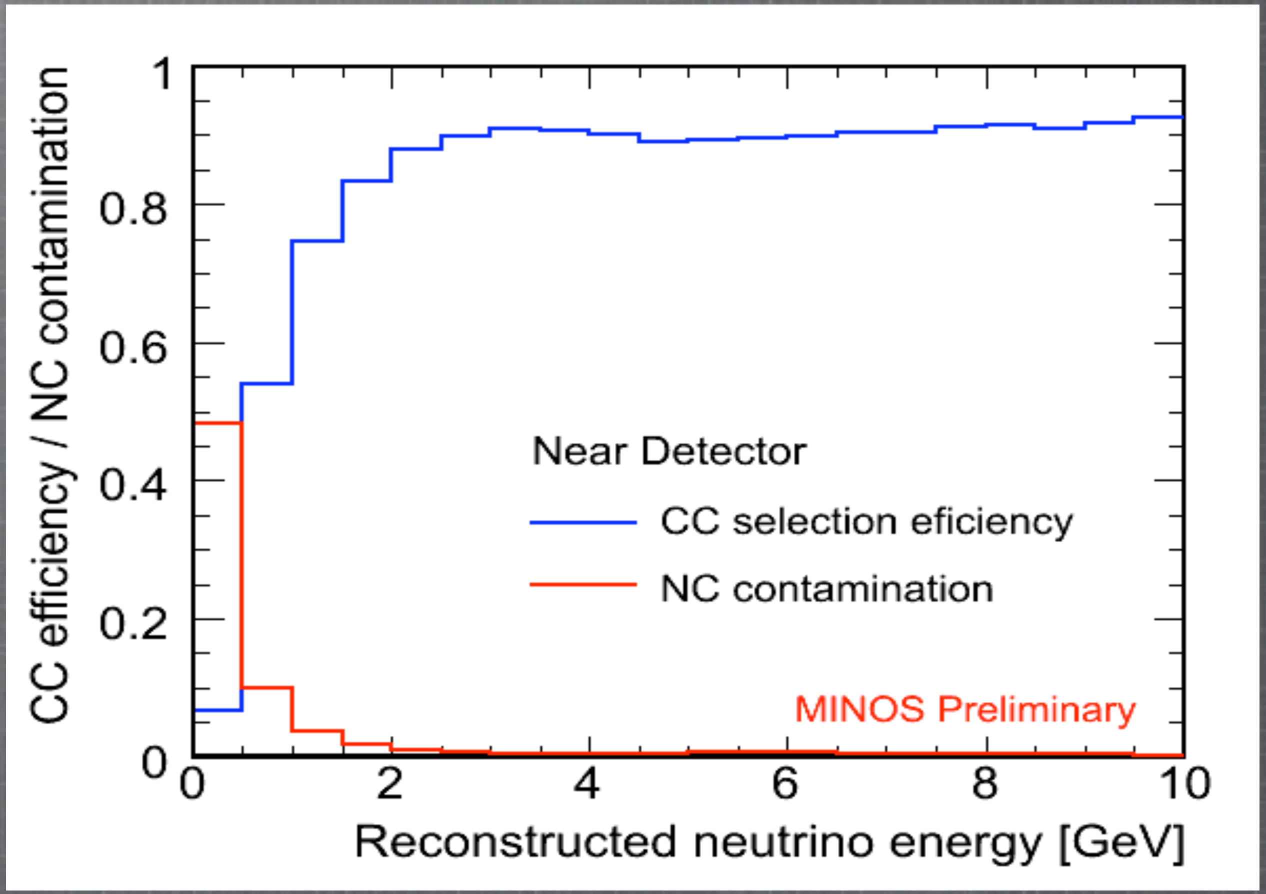






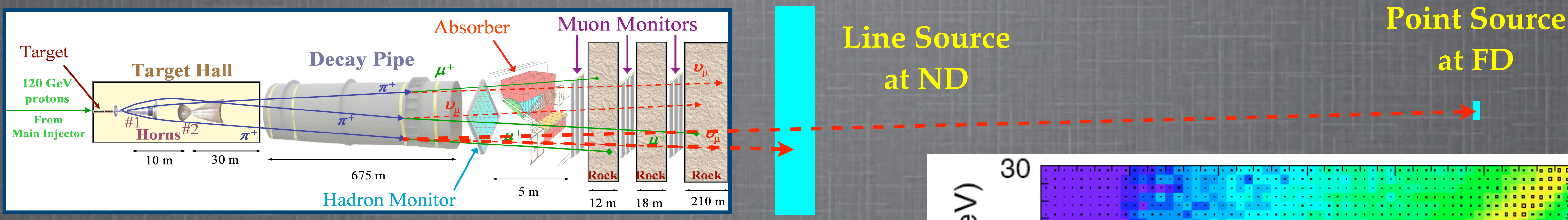
ν_μ CC Event Selection

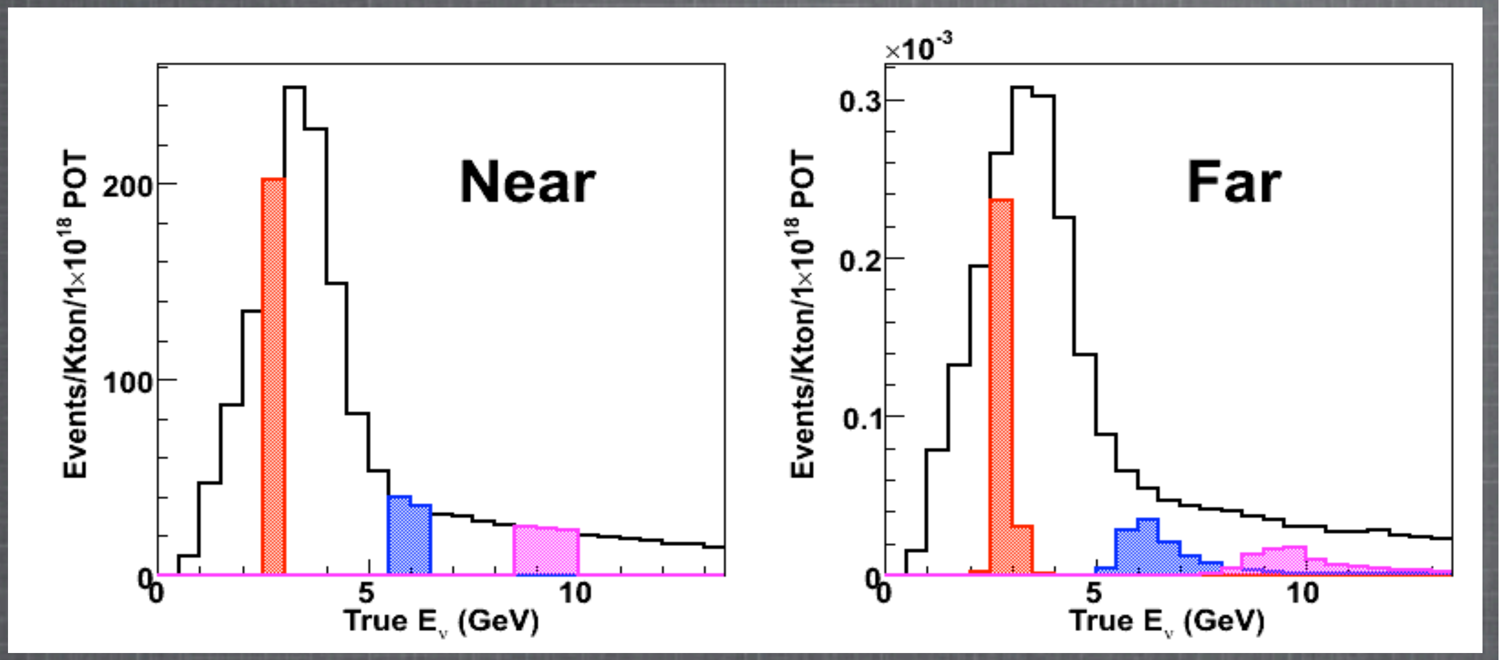


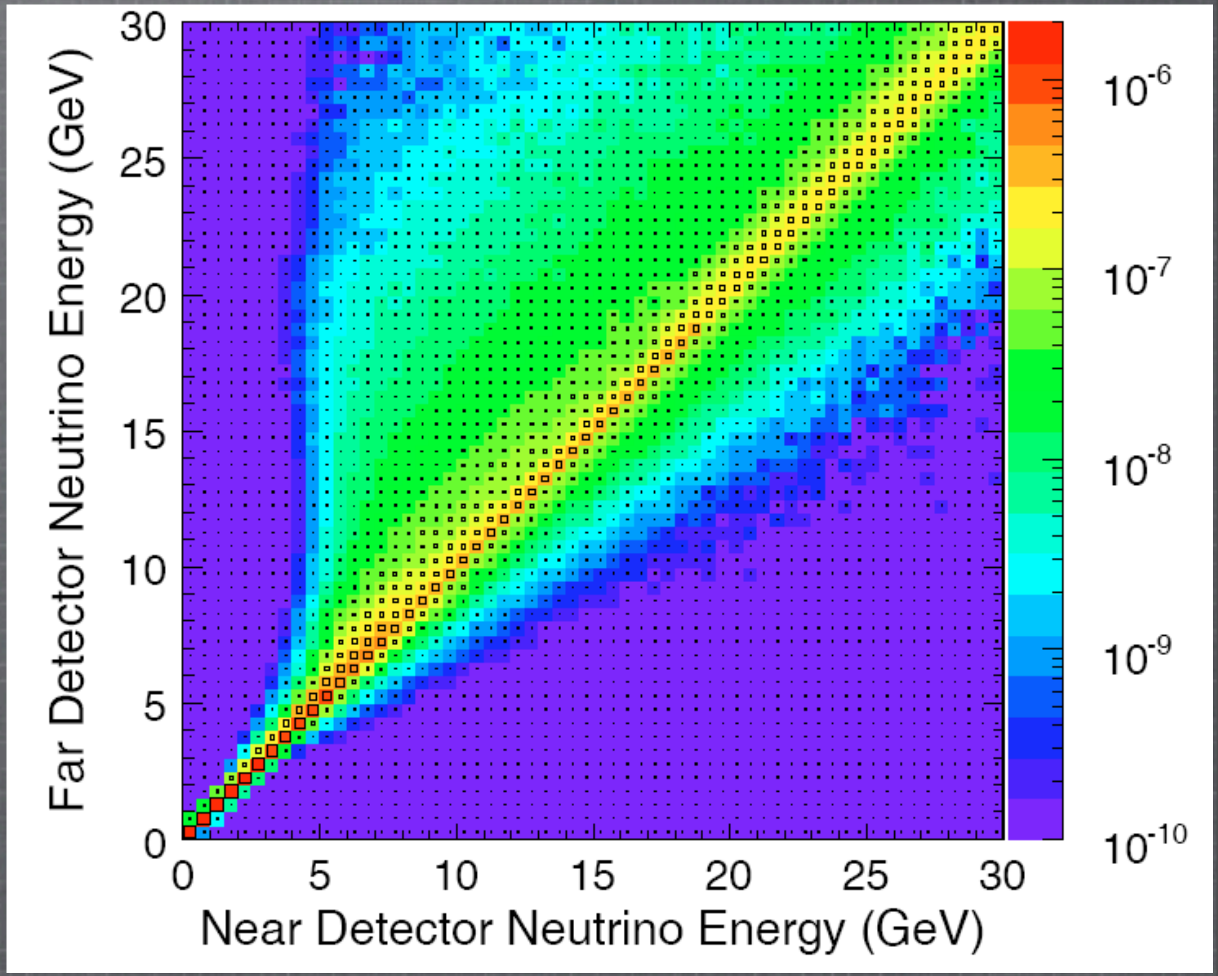


- Cut on separation parameter maximizes CC selection efficiency and minimizes NC background.
- Good agreement between data and MC above the CC/NC separation parameter cut.

Expected Far Detector Spectrum

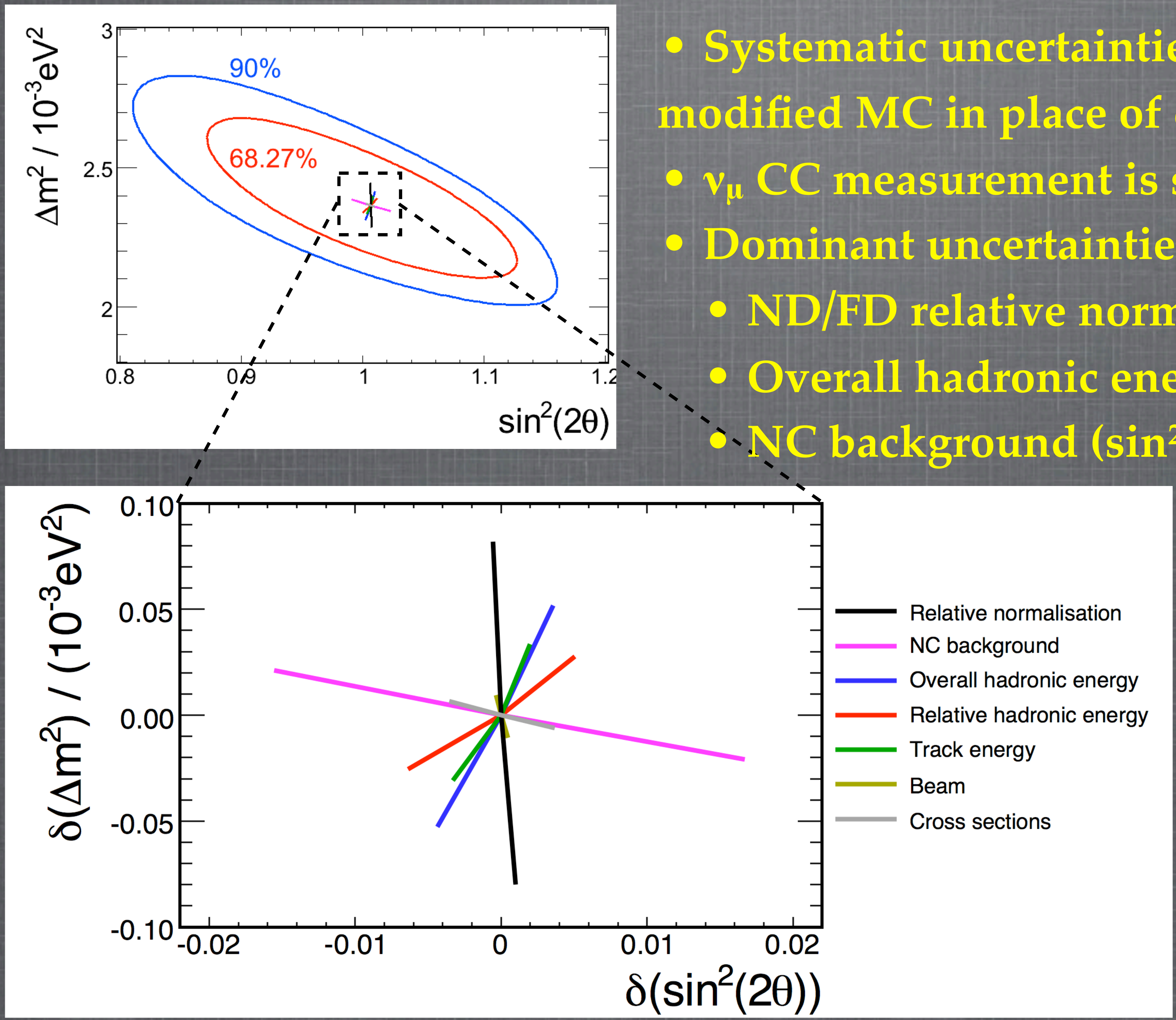






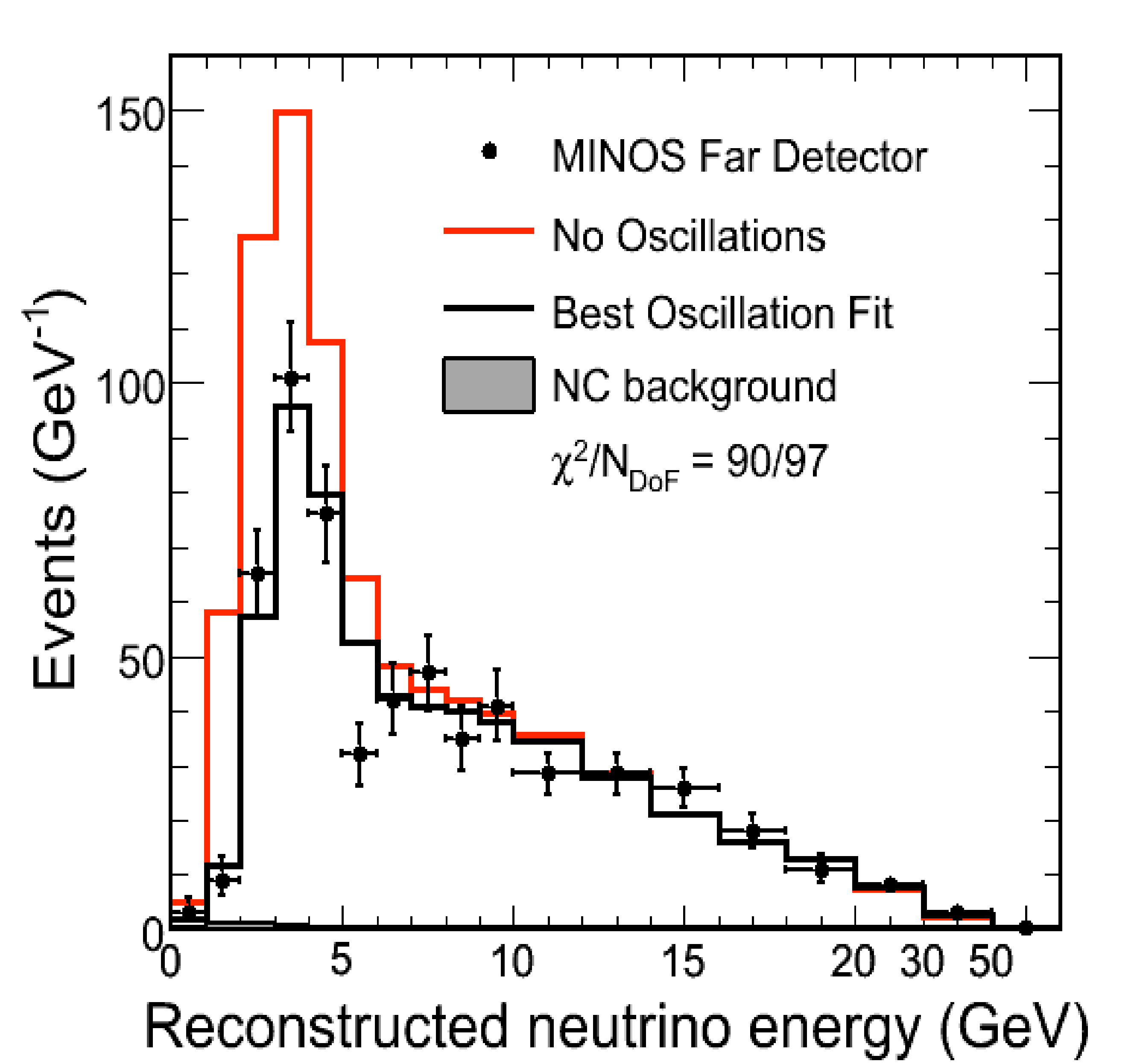
- Near detector spectrum is extrapolated to the far detector.
- Use MC to provide energy smearing and acceptance corrections.

Systematic Uncertainties



- Systematic uncertainties estimated by fitting modified MC in place of data.
- ν_μ CC measurement is statistics limited.
- Dominant uncertainties are:
  - ND/FD relative normalization (Δm^2)
  - Overall hadronic energy calibration (Δm^2)
  - NC background ($\sin^2(2\theta)$)

FD Energy Spectrum/Performing the Fit



Best fit:

$\Delta m^2 = 2.43 \times 10^{-3}$ eV^2

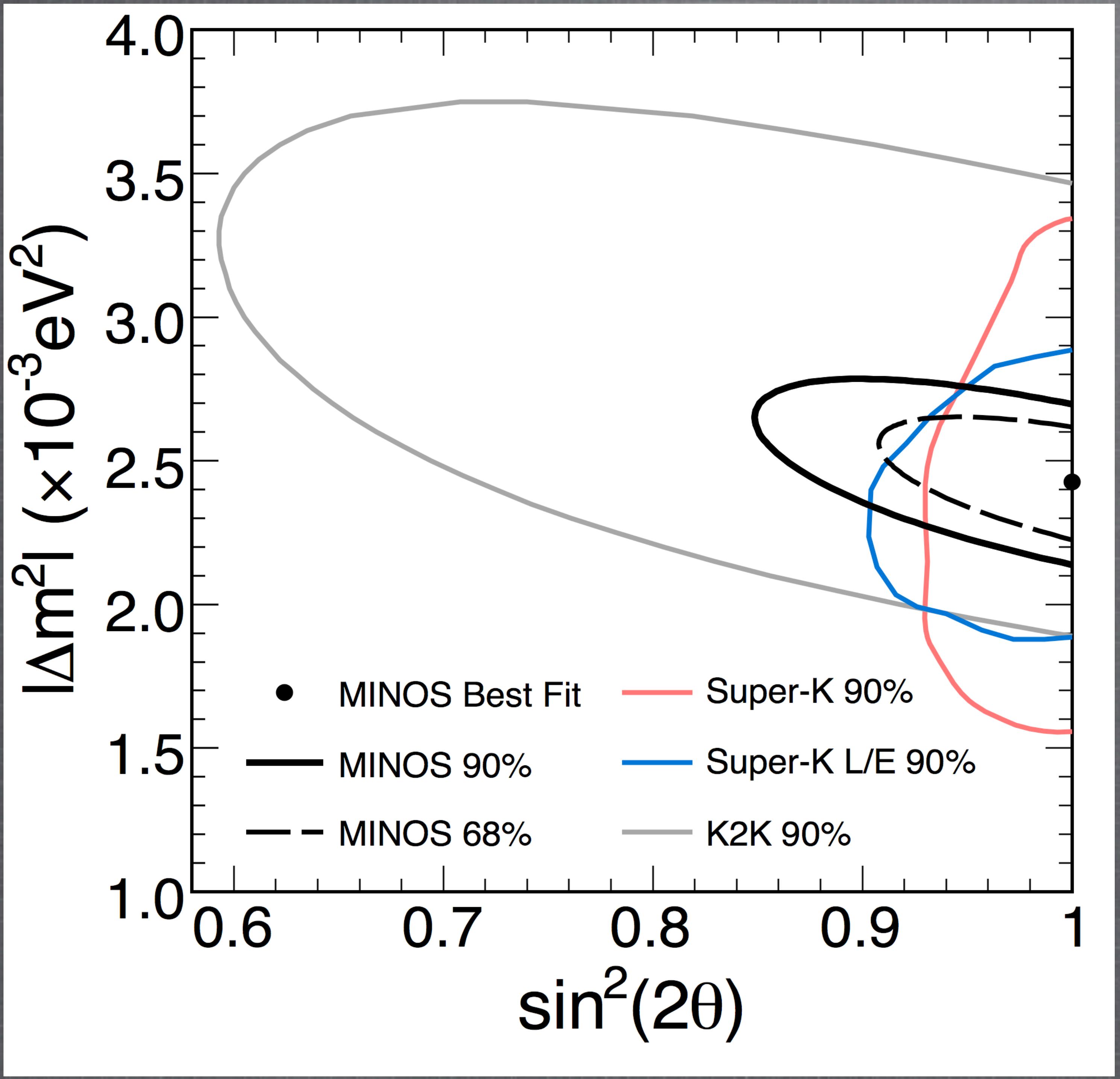
$\sin^2(2\theta) = 1.00$

- FD energy spectrum is only looked at after performing:
  - low-level data quality checks
  - procedural checks
- 848 events observed in the FD
- 1065 ± 60 expected with no oscillations
- We fit the energy distribution to the oscillation hypothesis:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\,\Delta m^2 L/E)$$

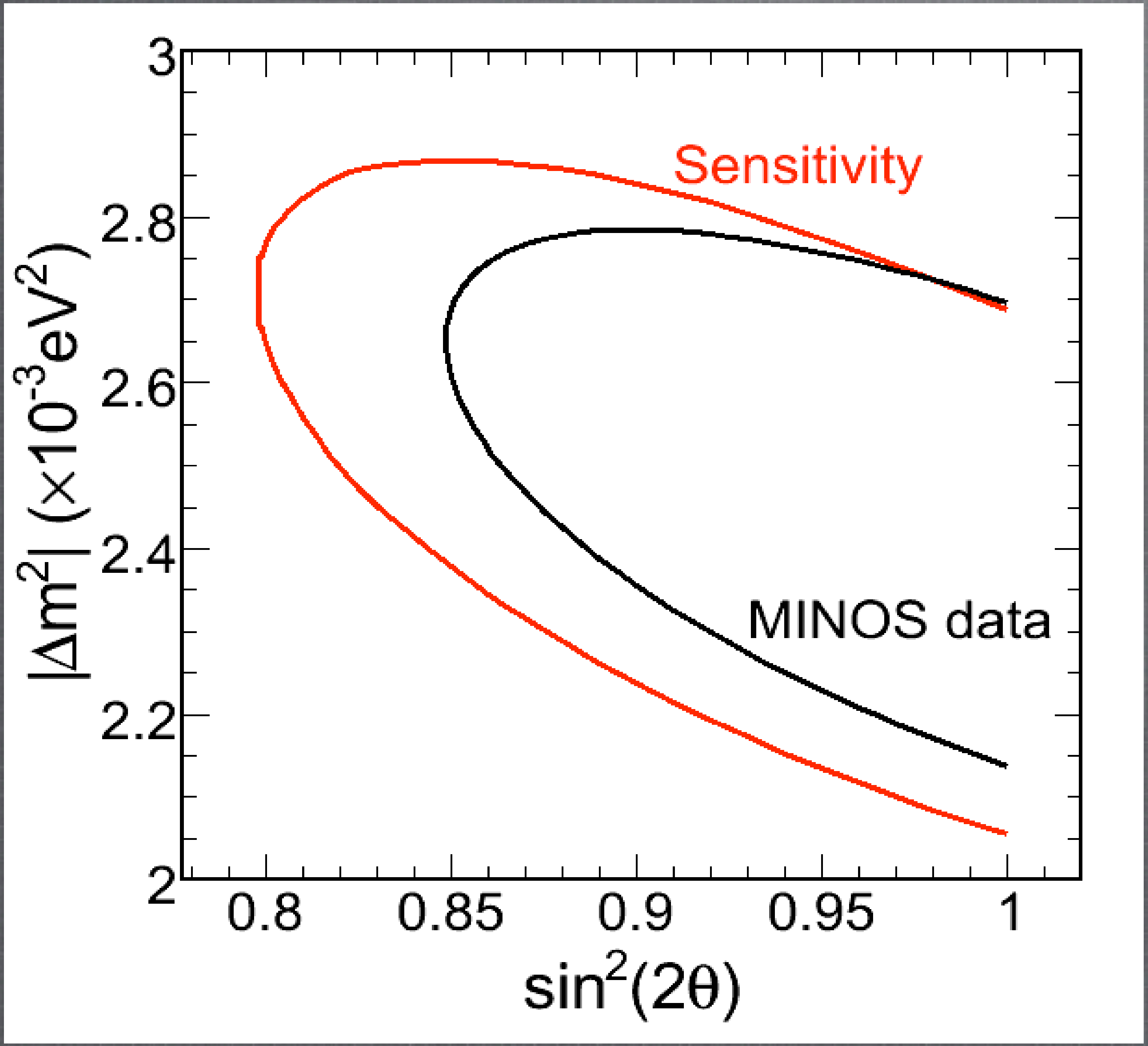
- The three largest systematic uncertainties are included as nuisance parameters
- $\sin^2(2\theta)$ is constrained to be ≤ 1.

Contours



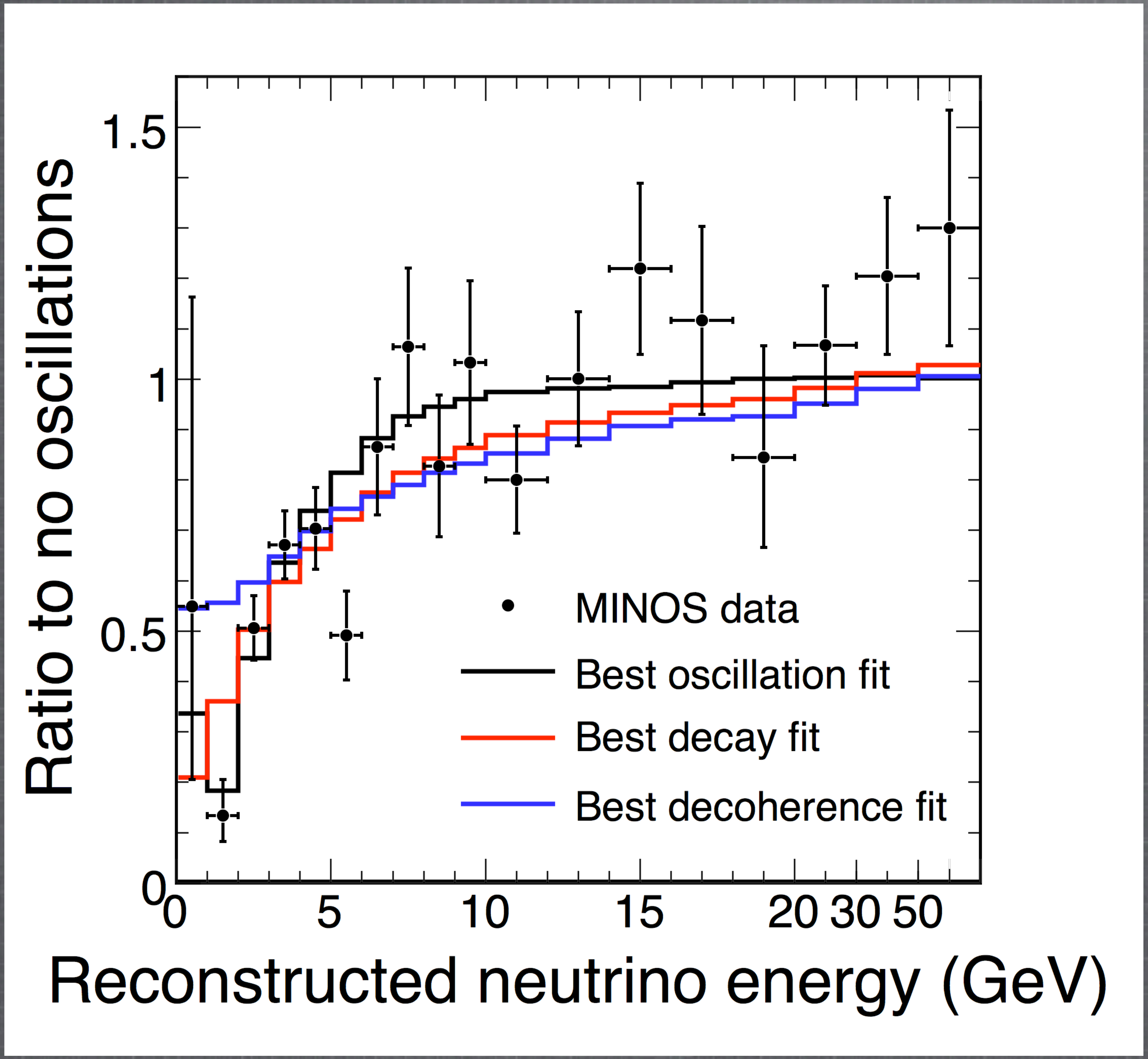
- **Constrained fit:**
  - $\Delta m^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (68% CL)
  - $\sin^2(2\theta) > 0.90$ (90% CL)
  - χ^2/ndof = 90/97
- **Unconstrained fit:**
  - $\Delta m^2 = 2.33 \times 10^{-3}$ eV^2
  - $\sin^2(2\theta) = 1.07$
  - $\Delta\chi^2 = -0.6$

Sensitivity



- Final contour is a bit smaller than the predicted sensitivity because $\sin^2(2\theta)$ falls in the unphysical region.
- A study shows that 26.5% of unconstrained fits have a fit value of $\sin^2(2\theta) \geq 1.07$
- Feldman-Cousins study indicates that our contours are slightly conservative.

Alternative Hypotheses



Decay:

$P_{\mu\mu} = \sin^4\theta + \cos^4\theta \exp(-\alpha L/E)$

χ^2/ndof = 104/97

$\Delta\chi^2 = 14$

Disfavored at 3.7 σ

Decoherence:

$P_{\mu\mu} = 1 - \frac{1}{2} \sin^2(2\theta) (1 - \exp(-\mu^2 L/2E))$

χ^2/ndof = 123/97

$\Delta\chi^2 = 33$

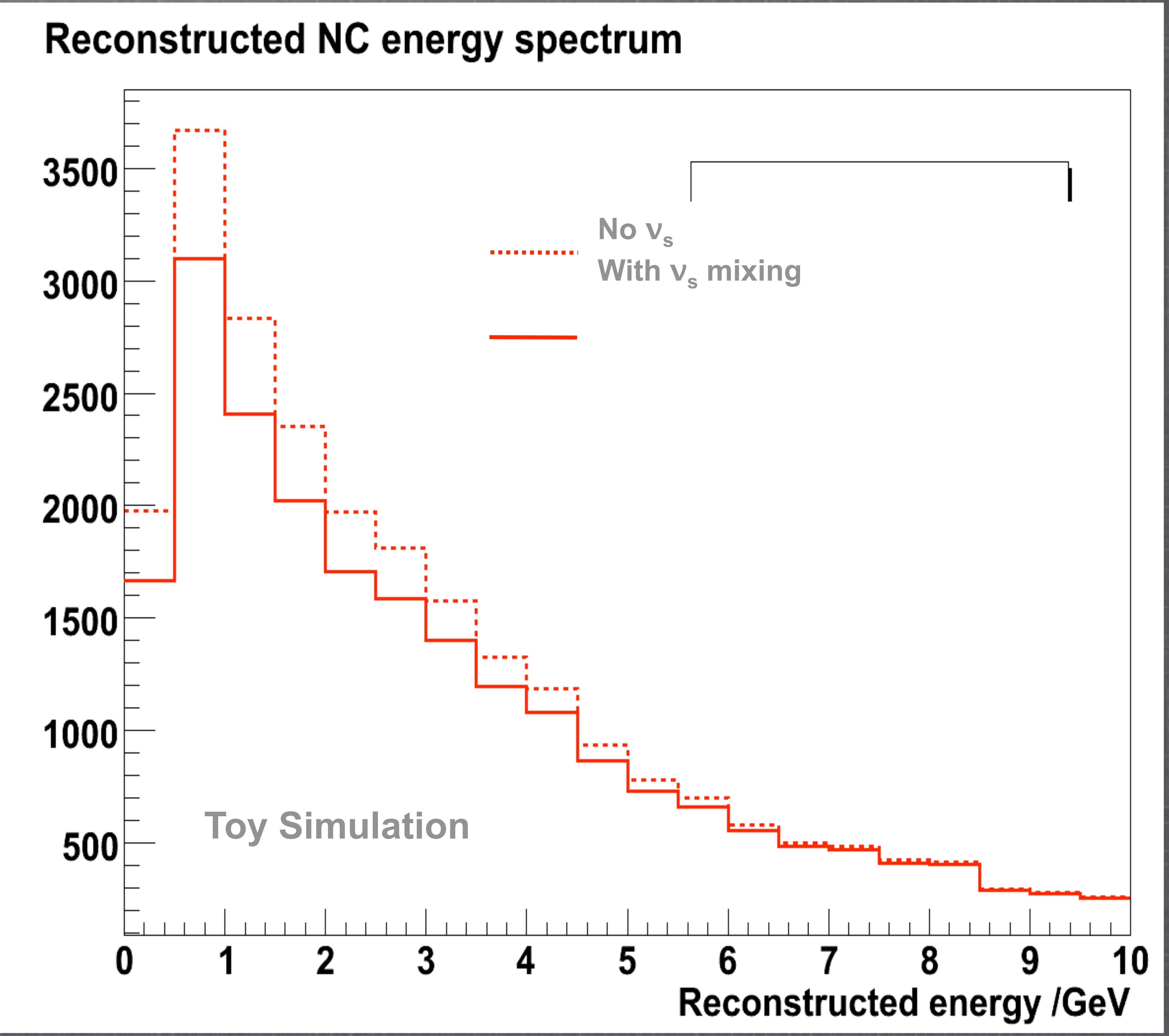
Disfavored at 5.7 σ

NC Analysis

The search for sterile neutrinos

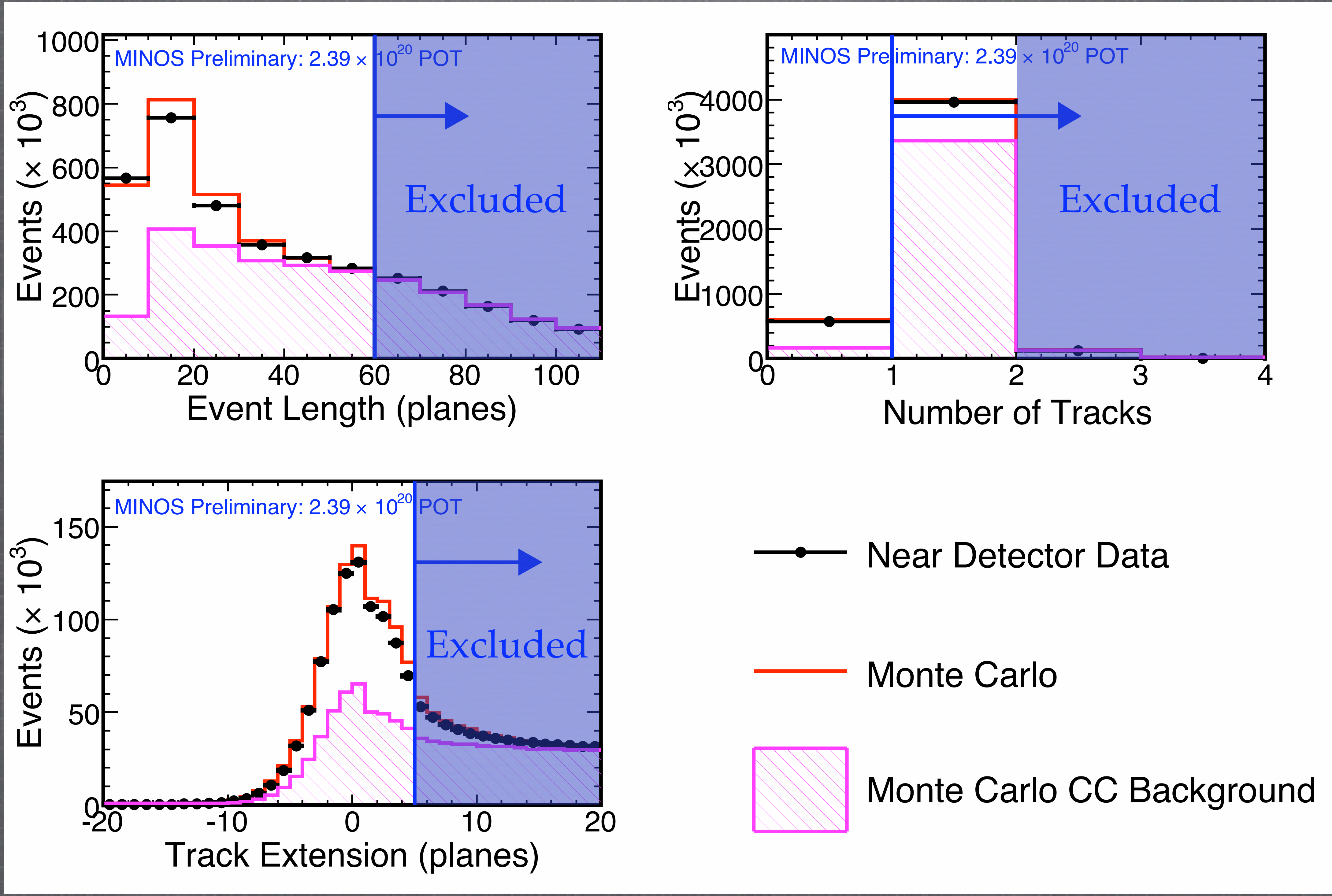
Why NC Events?

- Oscillations of ν_μ into ν_s would result in a depletion of both CC and NC events in the FD.
- Depletion of CC events could be masked by $\nu_\mu \rightarrow \nu_\tau$. Depletion of NC events can only be explained by ν_s, since NC events are "flavor-blind".

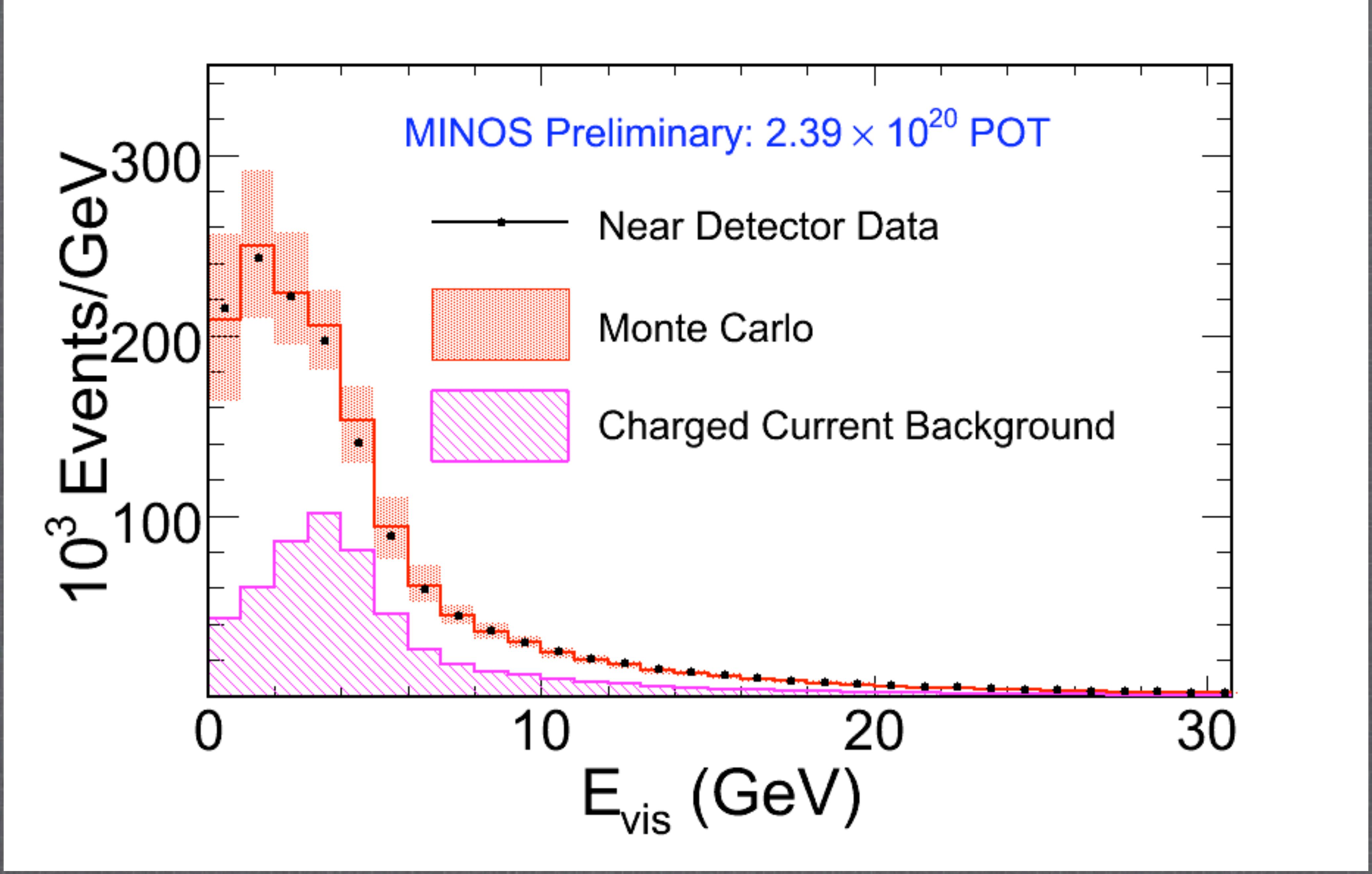


NC Event Selection in the ND

Select reconstructed "shower-like" events that fall within a fiducial volume.



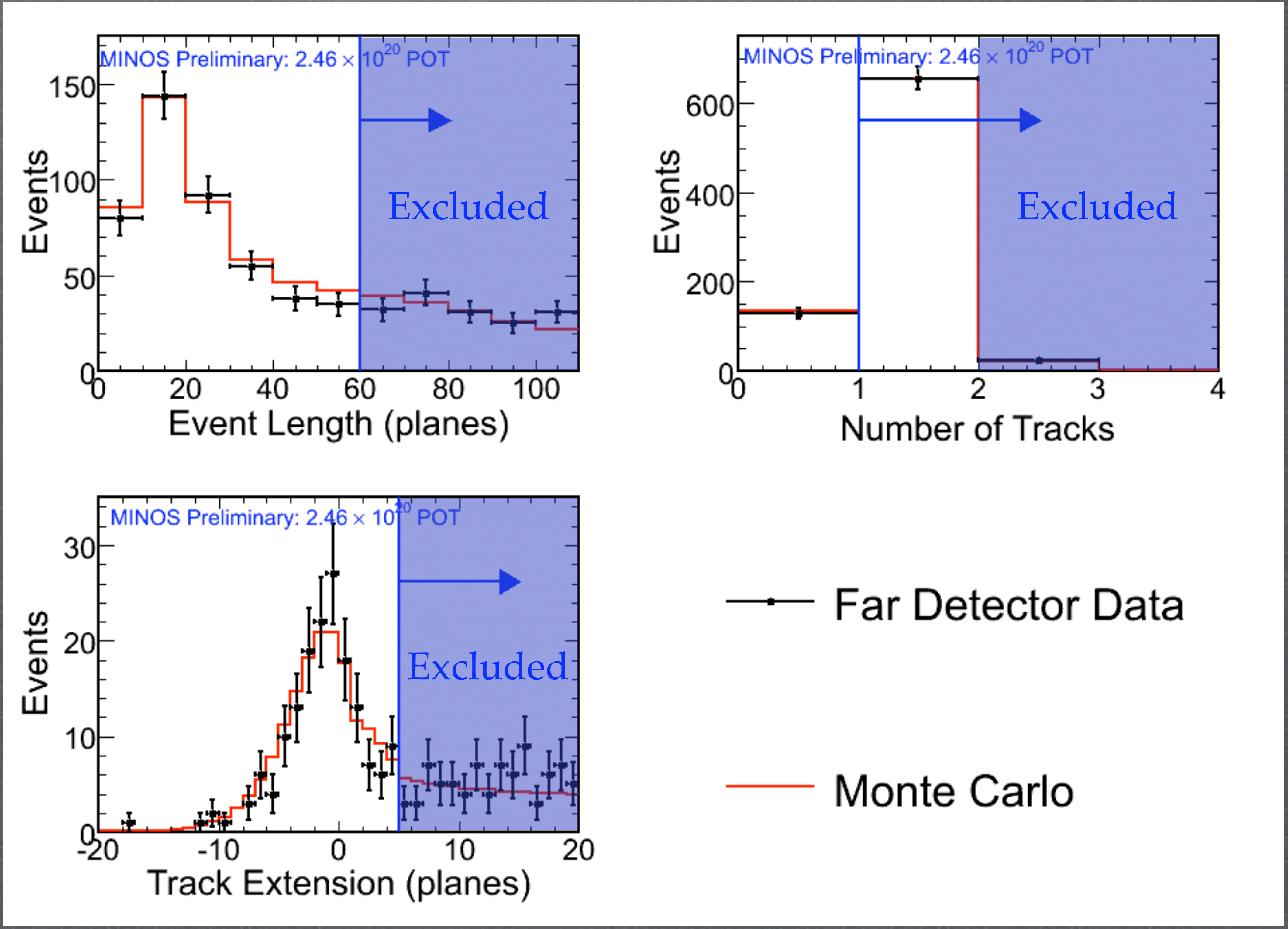
Expected Far Detector Spectrum



NC event selection efficiency is 90%, purity is 60%.

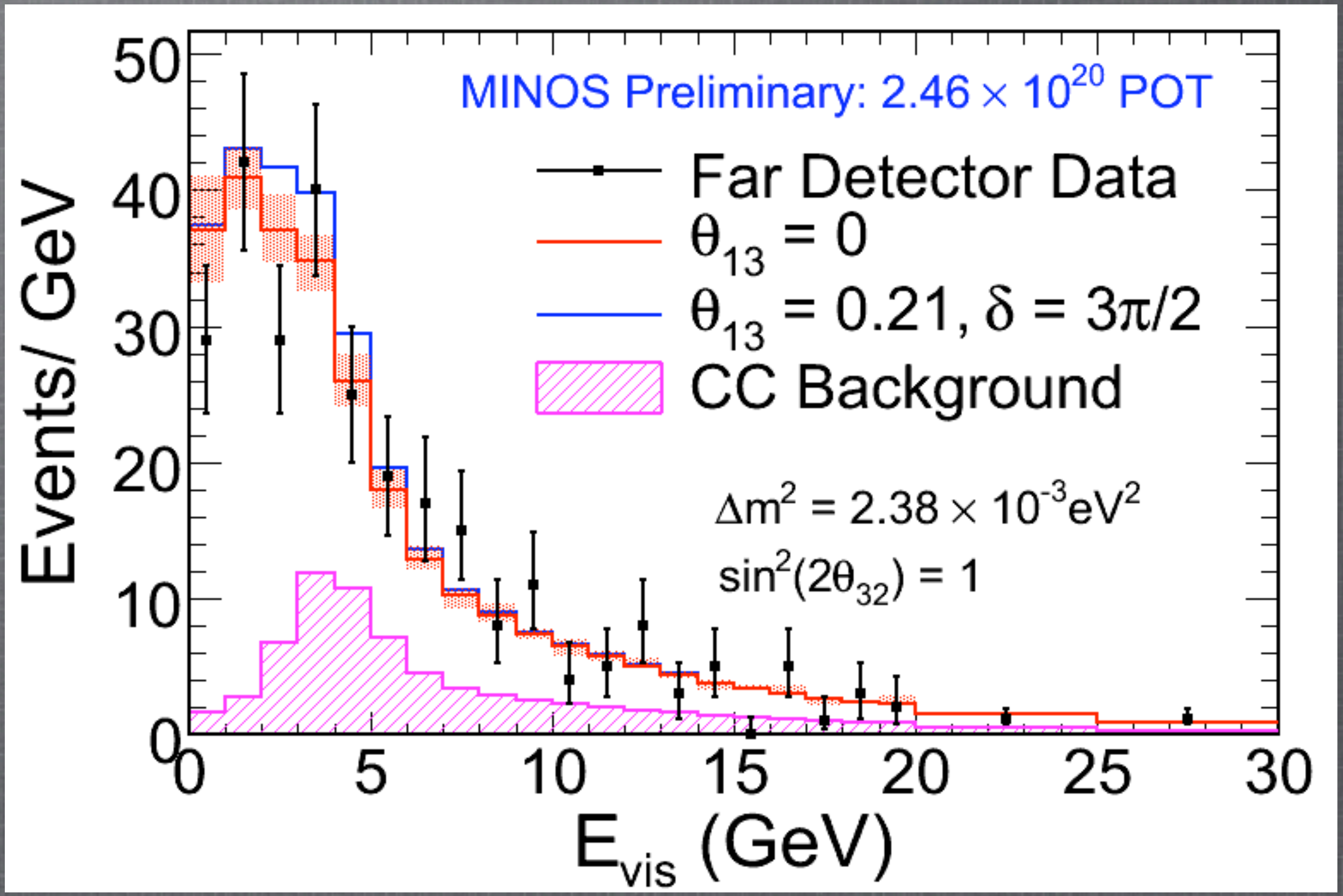
NC Event Selection in the FD

- Identical cuts are made in FD as in ND.
- MC oscillated with 2007 MINOS CC best fit values of $\Delta m^2 = 2.38 \times 10^{-3}\ \mathrm{eV}^2$ and $\sin^2(2\theta) = 1$.



3-Flavor Analysis Results

- $\Delta m^2_{32} = 2.38 \times 10^{-3}\ eV^2$
- $\Delta m^2_{21} = 7.59 \times 10^{-5}\ eV^2$
- $\sin^2(2\theta_{12}) = 0.61$ KamLAND + SNO
- $\sin^2(2\theta_{23}) = 1$
- $\theta_{13} = 0$ or 0.21 CHOOZ limit normal MH, $\delta = 3\pi/2$



Data/MC Comparison for $\theta_{13} = 0$

Energy Range (GeV)	0 - 3	0 - 5	0 - 120
Data	100	165	291
MC	115.16 ± 7.67	175.92 ± 10.42	292.63 ± 15.02
Significance (σ)	1.15	0.65	0.10

- For $E_{vis} < 3$ GeV, $f_s < 35\%$ at 90% CL.
- For $E_{vis} < 120$ GeV, $f_s < 17\%$ at 90% CL.

Other Finalized Analyses

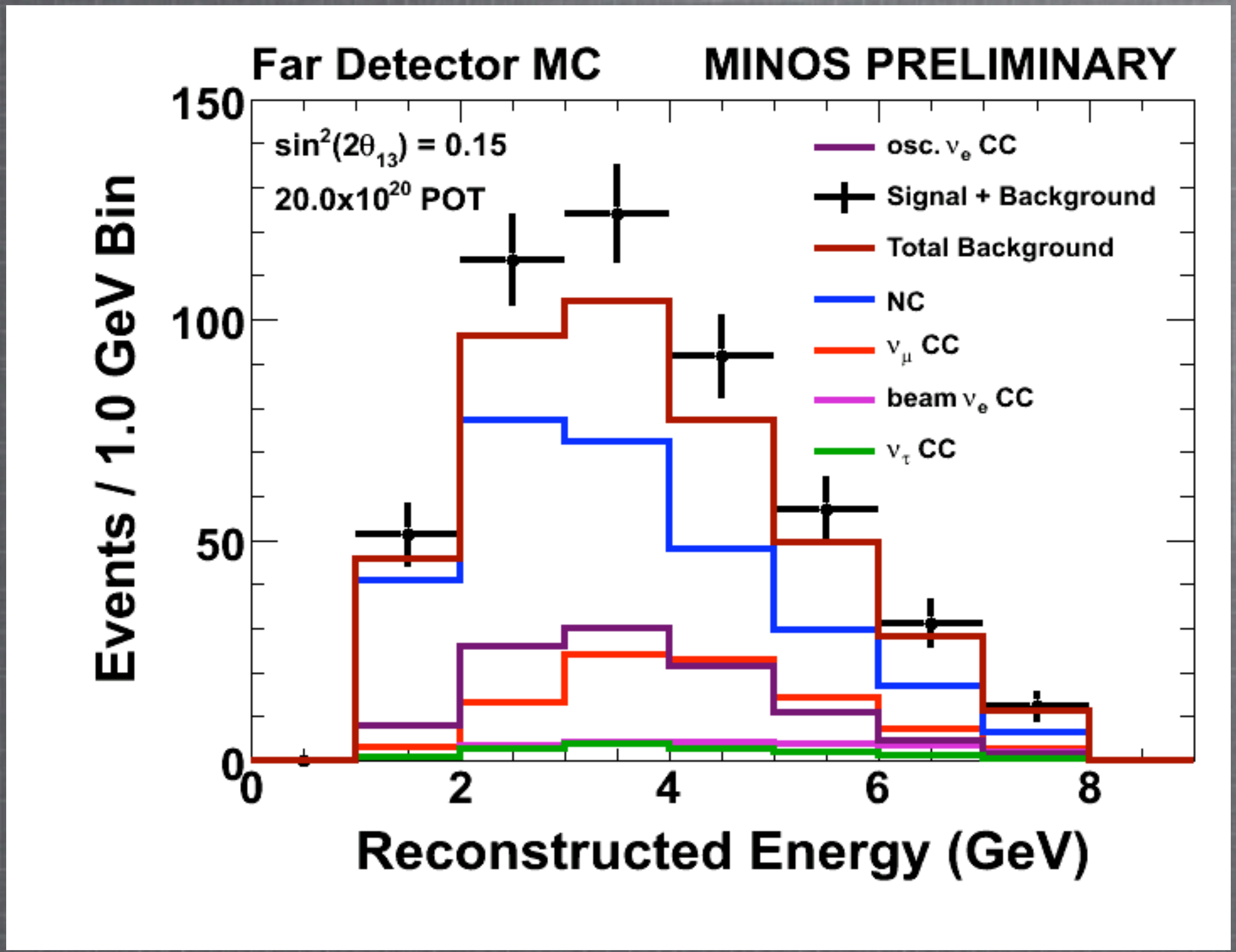
- “**Sudden stratospheric warmings seen by an underground detector**”: correlation between FD cosmic muon rate and temperature changes in the upper atmosphere.
- “**Testing Lorentz Invariance and CPT Conservation with MINOS Near Detector Neutrinos**”: search for a sidereal signal in the MINOS ND. Upper limits set on individual SME Lorentz and CPT violating terms.
- “**Observation of deficit in NuMI neutrino-induced rock and non-fiducial muons in MINOS far detector and measurement of neutrino oscillation parameters**”: see poster by Aaron McGowan

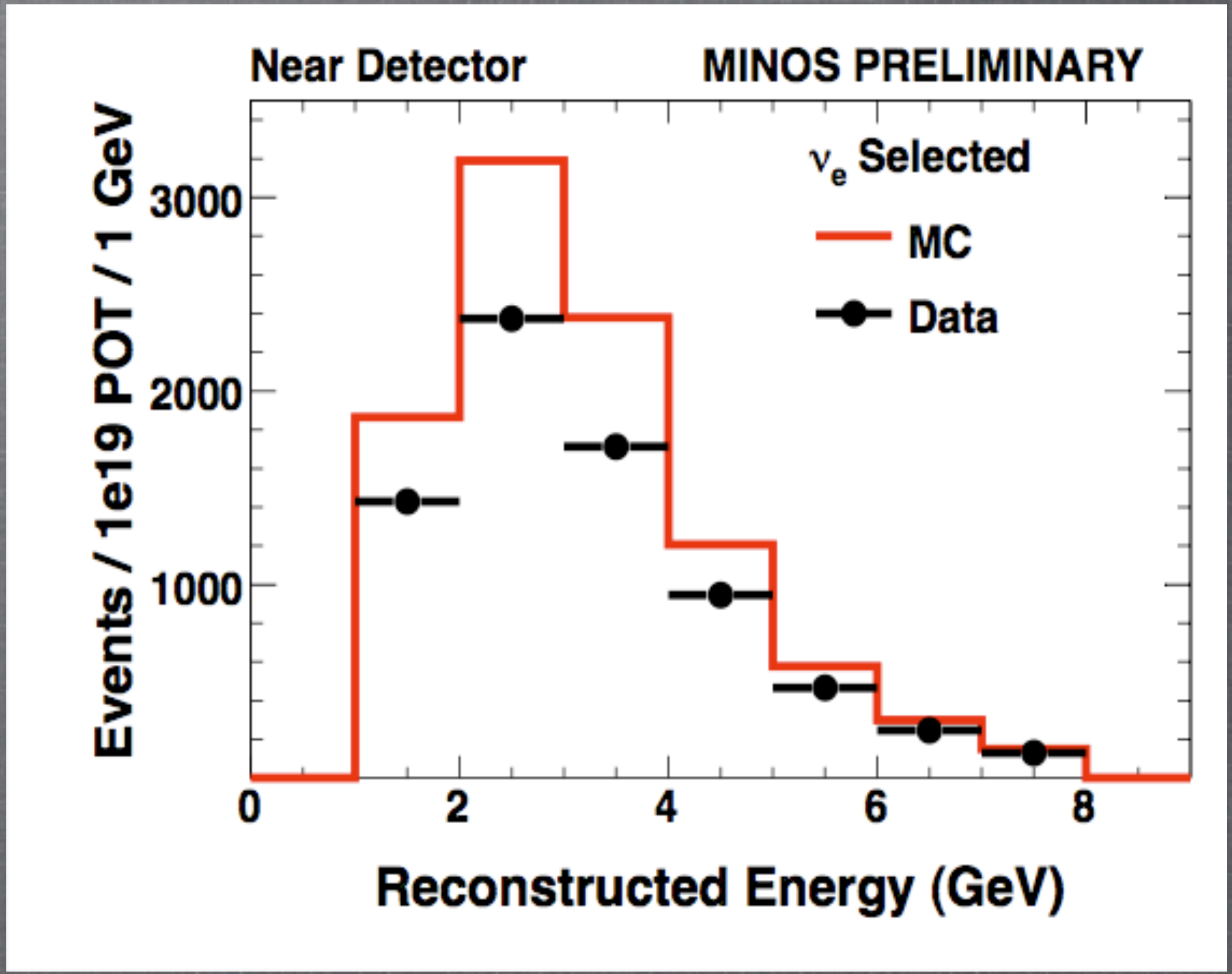
ν_e CC Analysis

The search for ν_e appearance

**** See posters by Steven Cavanaugh and Lisa Whitehead for more details!**

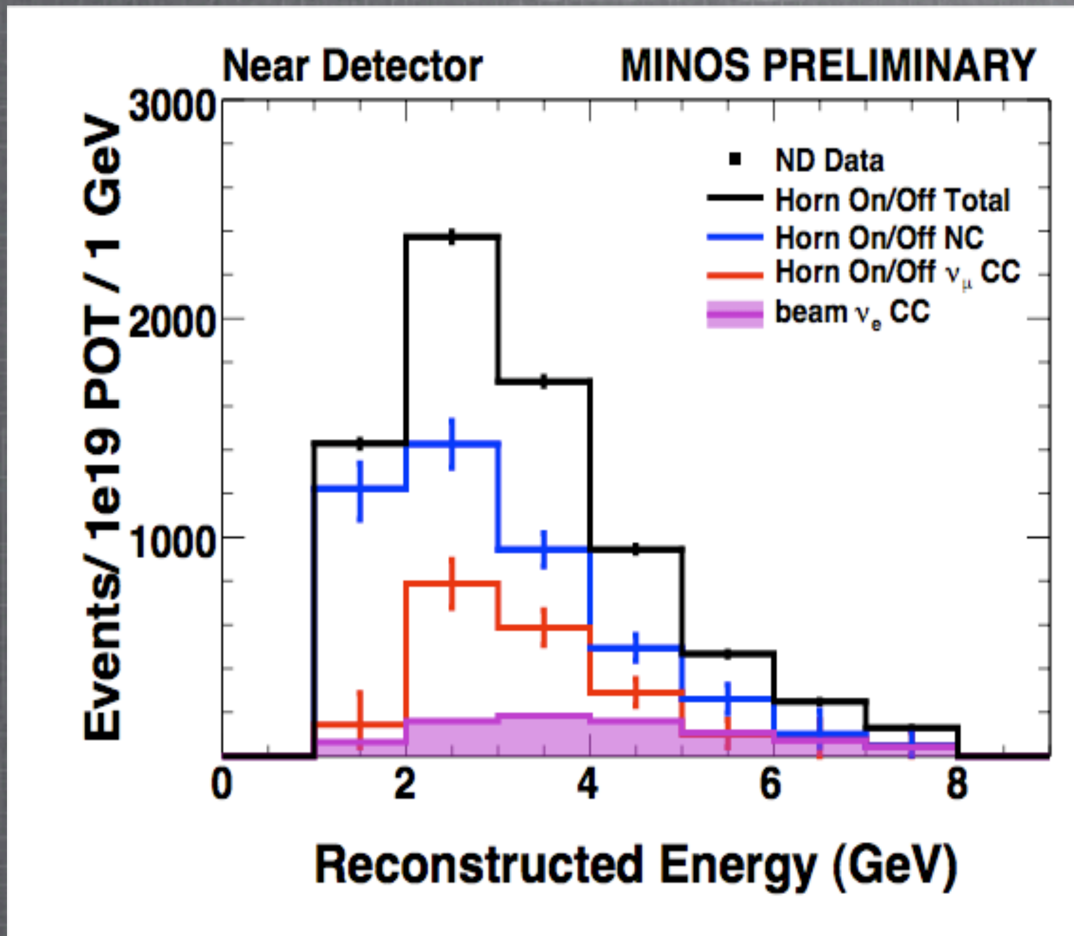
ν_e Background Estimates

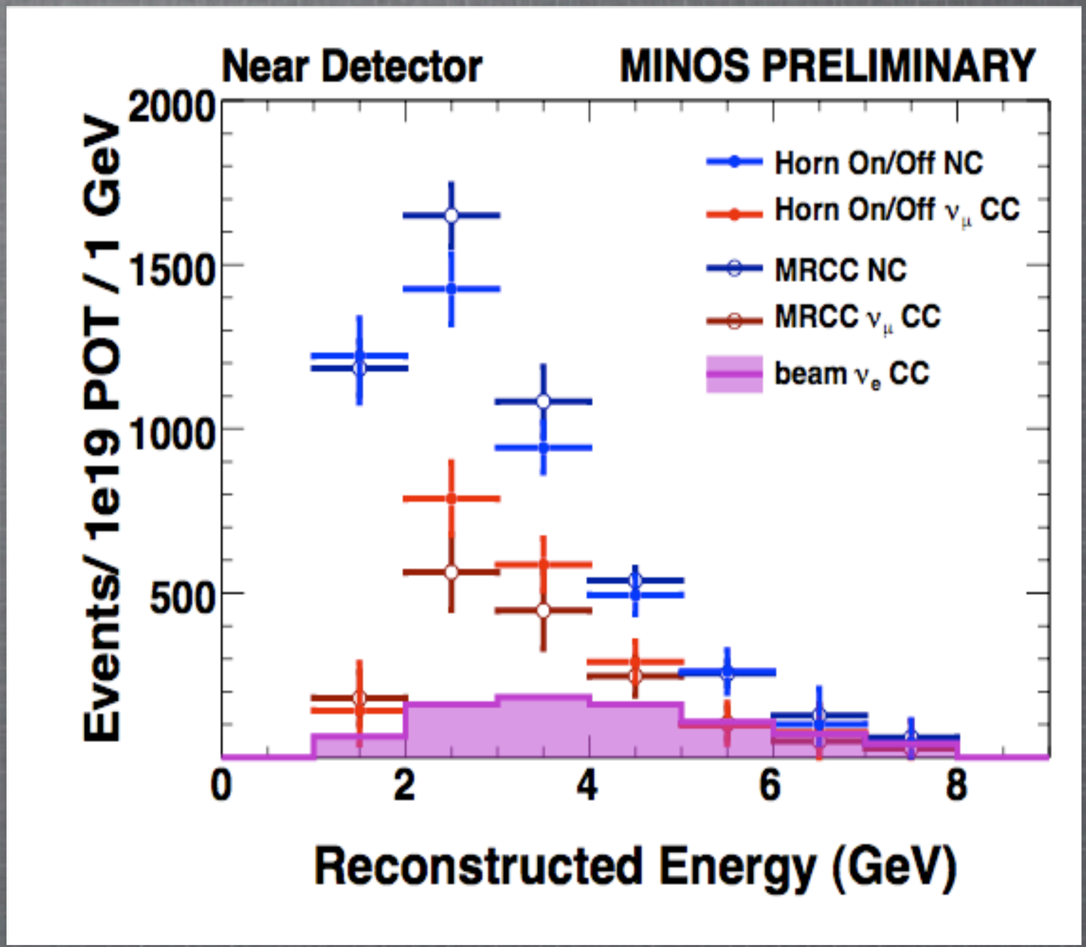




- Measurement dominated by backgrounds: at the CHOOZ limit, 12 ν_e events are expected with 42 background events (for 3.25×10^{20} POT).
- Dominant backgrounds are NC and high-y ν_μ CC events.
- We see a very large discrepancy between selected ν_e ND MC and data events.

ν_e Data-Driven Background Studies



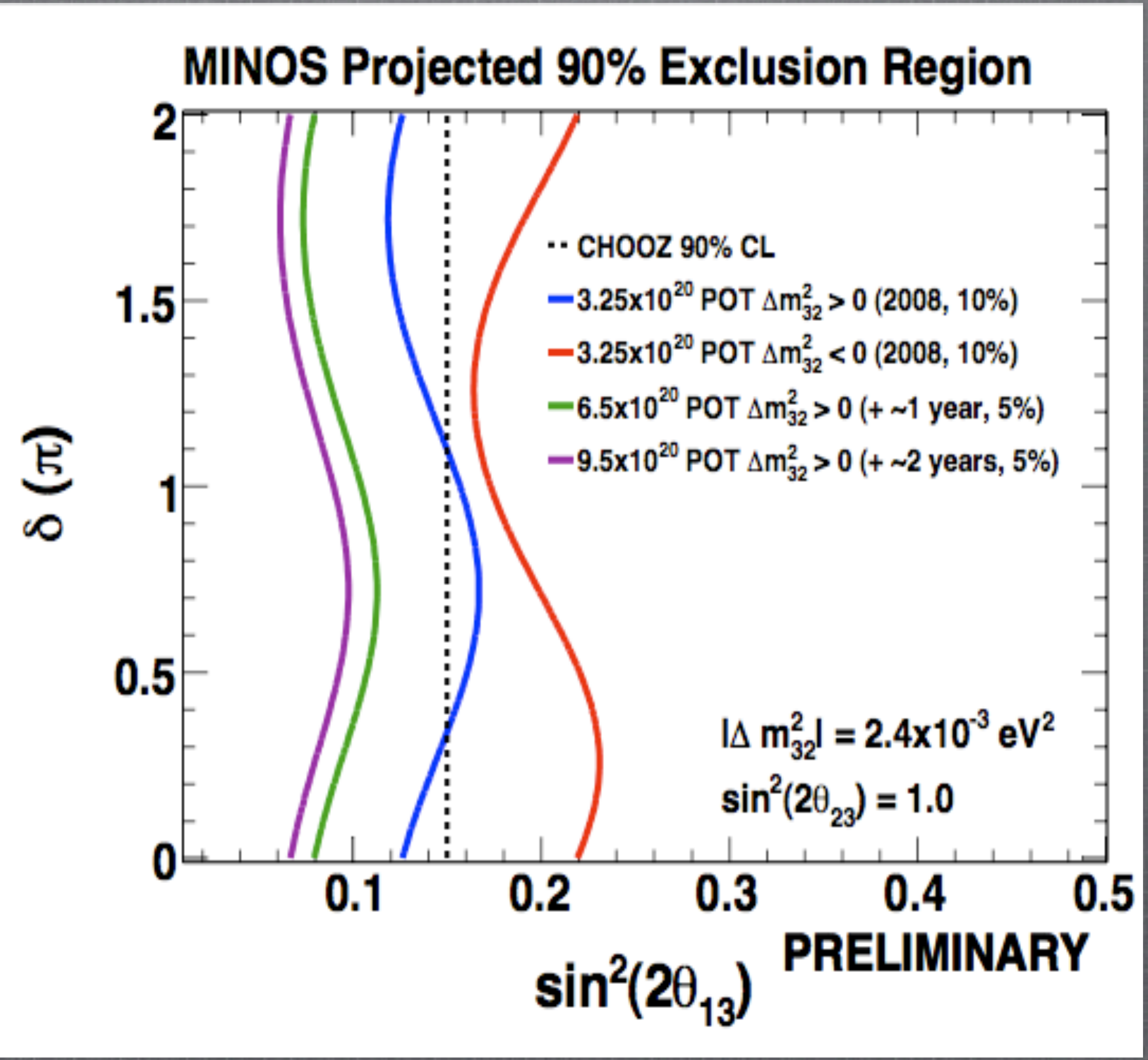


Estimate	Signal ν_e	Total BG	NC	ν_μ CC	Beam ν_e	ν_τ CC
Horn On/Off	12	42	29	8	3	2
MRCC	12	43	32	6	3	2

$\sin^2(2\theta_{23}) = 1.0$
$\Delta m^2_{32} = 2.4 \times 10^{-3}\ \mathrm{eV}^2$
$\sin^2(2\theta_{13}) = 0.15$
no matter effects
3.25×10^{20} POT

- Horn On/Off - constrain the relative ratios of NC and ν_μ CC background events in two different beam configurations.
- Muon removed hadron showers from ν_μ CC (MRCC).

ν_e Sensitivity



- Projected limits for expected MINOS integrated exposures for the next few years.
- Inverted hierarchy (in red) shown only for lowest exposure.
- MINOS can improve upon the CHOOZ limit by ~x2.

Other Analyses in the Works

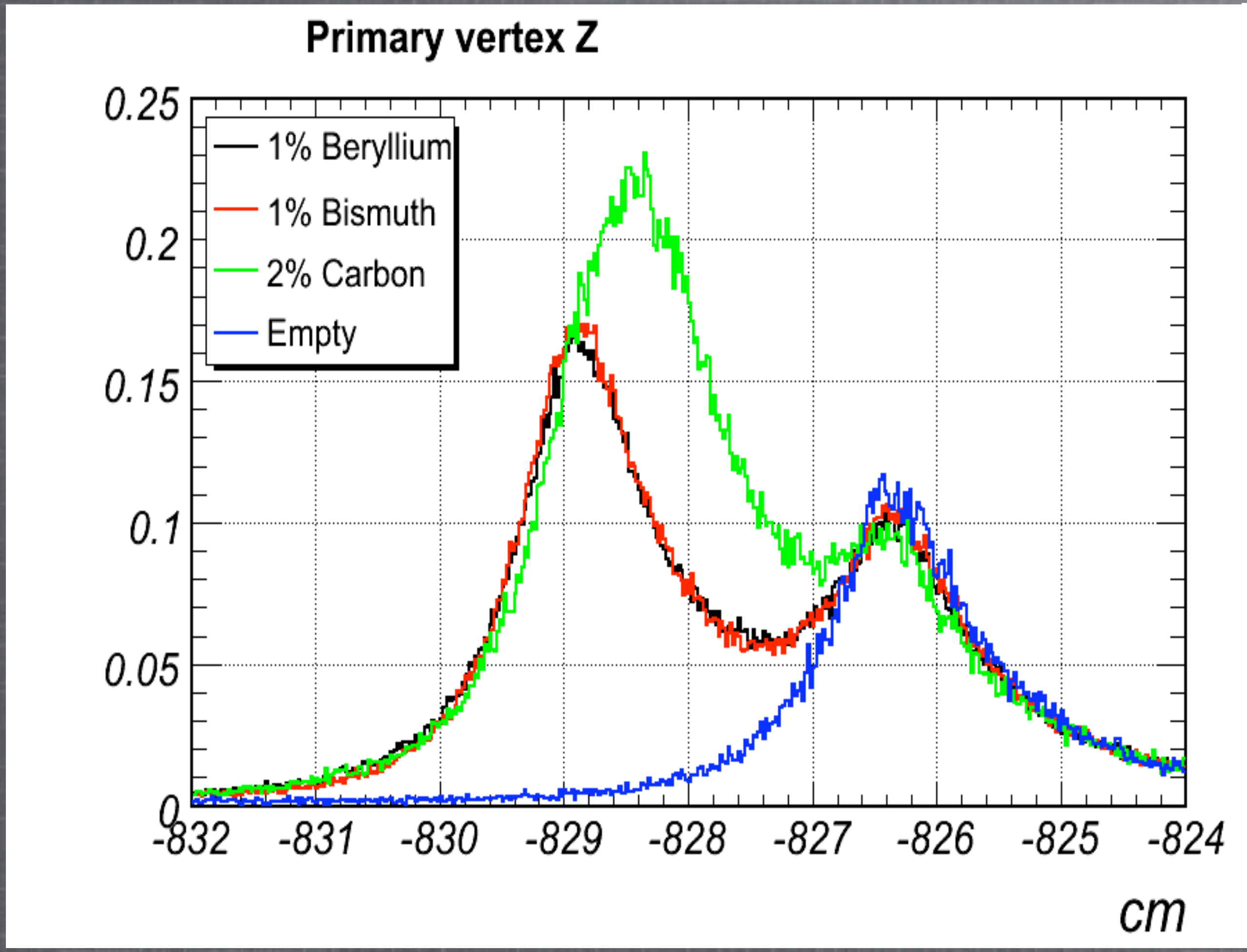
- Anti-neutrino oscillation measurements
- ND measurements:
  - Inclusive CC cross-section and structure functions
  - mA extraction from quasi-elastic events
  - NC coherent scattering on Fe
  - Cosmic rays

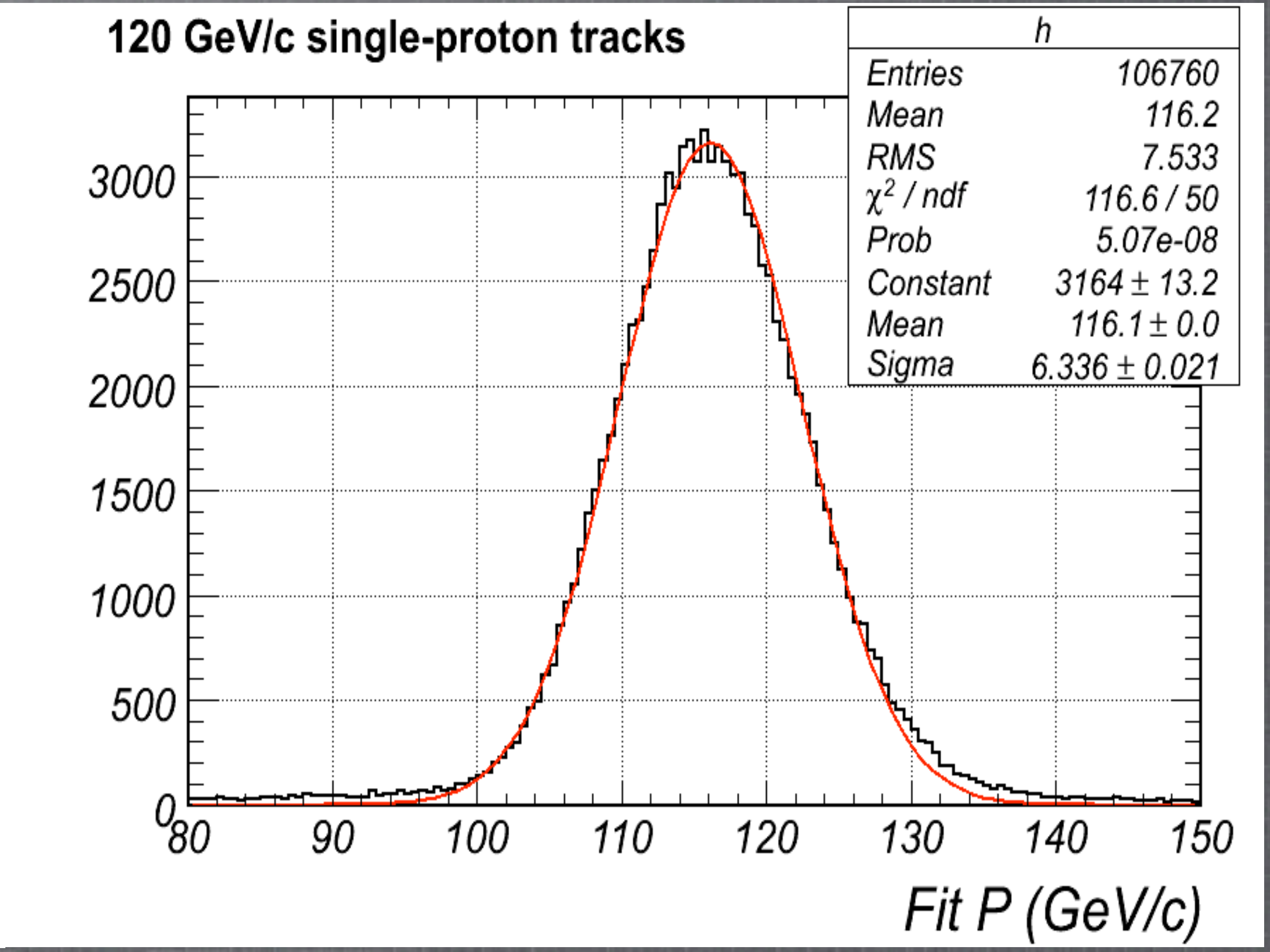
Conclusions

- 2007-08 has been a very productive year for MINOS!
- Latest ν_μ CC analysis results (3.36×10^{20} POT):
  - $\Delta m^2 = (2.43 \pm 0.13) \times 10^{-3}\ eV^2$ (68% CL),
  - $\sin^2(2\theta) > 0.90$ (90% CL),
  - Decay and decoherence models disfavored at 3.7 and 5.7 σ respectively.
- NC analysis results (2.46×10^{20} POT): fraction of disappearing NC events < 0.17 at 90% CL.
- Great progress in understanding the backgrounds and systematics in the νe appearance measurement; first results are expected later this year.
- Results from MIPP expected later this year, expected uncertainty on ν flux is ~15%.
- Many ND ν interaction measurements also expected later this year.
- **Thanks to FNAL AD, CD, and administration for all their hard work and support!**

Backup Slides

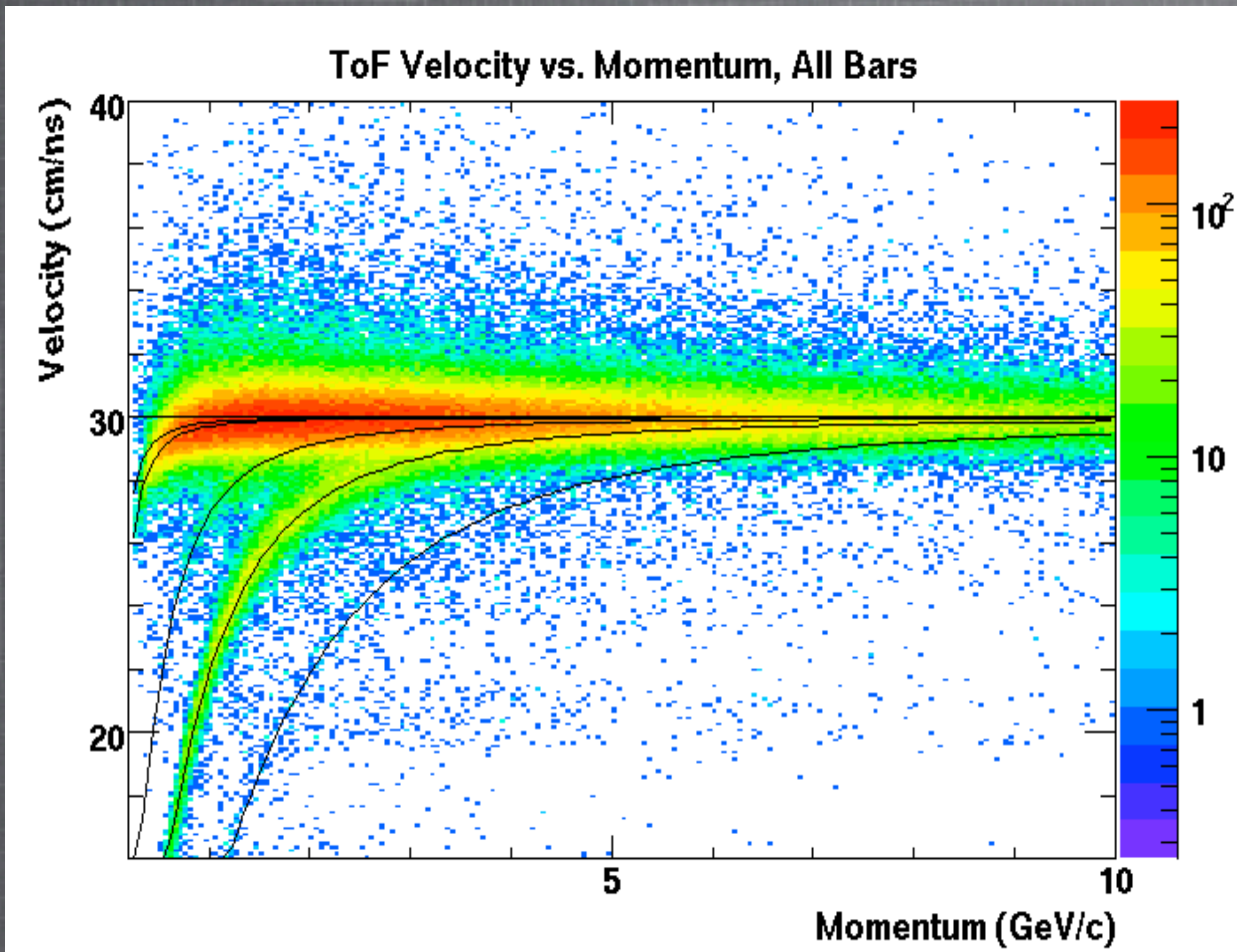
MIPP Performance

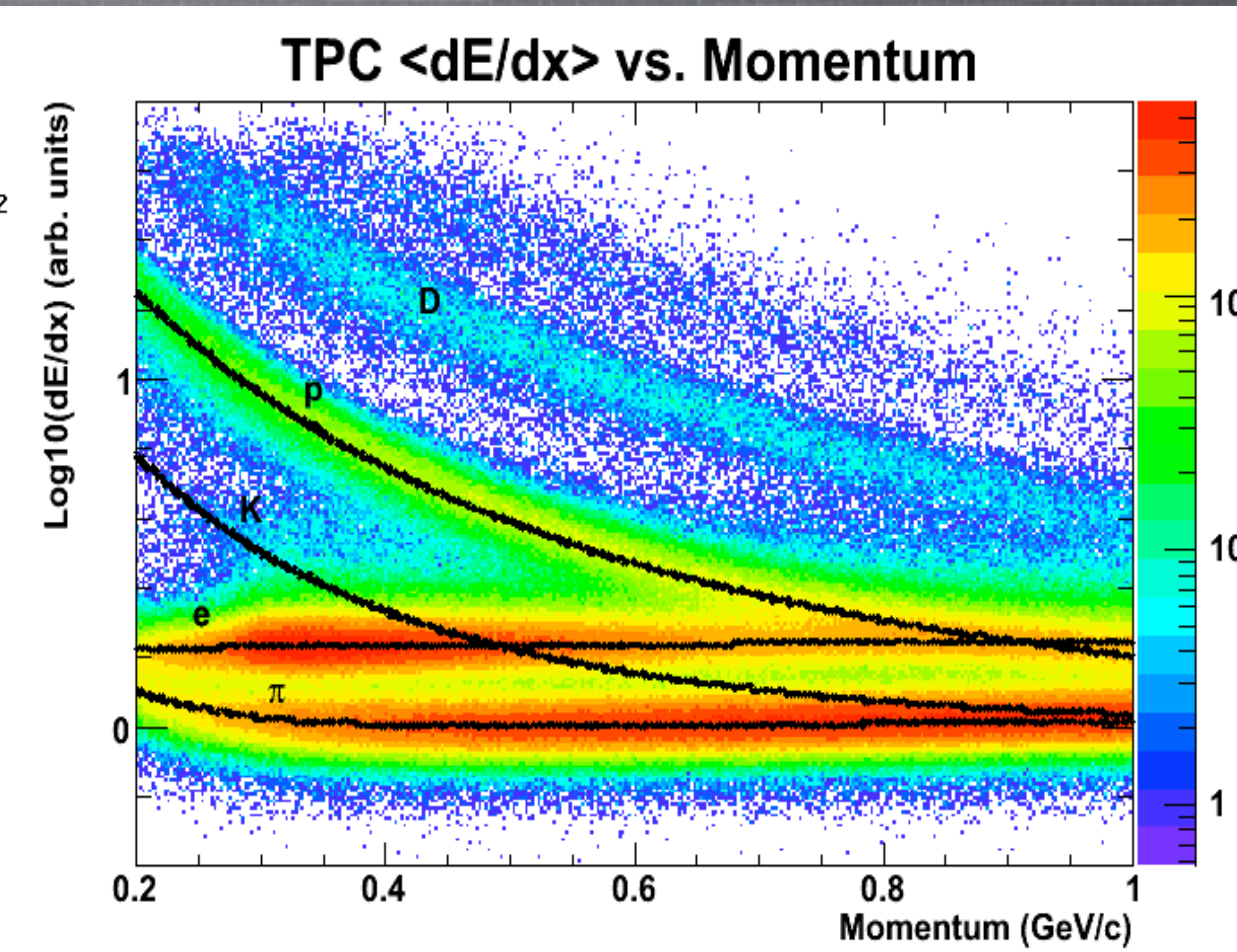




- Momentum resolution is ~5% at 120 GeV/c, much better at lower momenta.
- Vertex resolution is ~8 mm in the beam direction, ~2 mm transverse.
- Reconstructed momentum appears to be systematically low by ~2%.

MIPP Performance

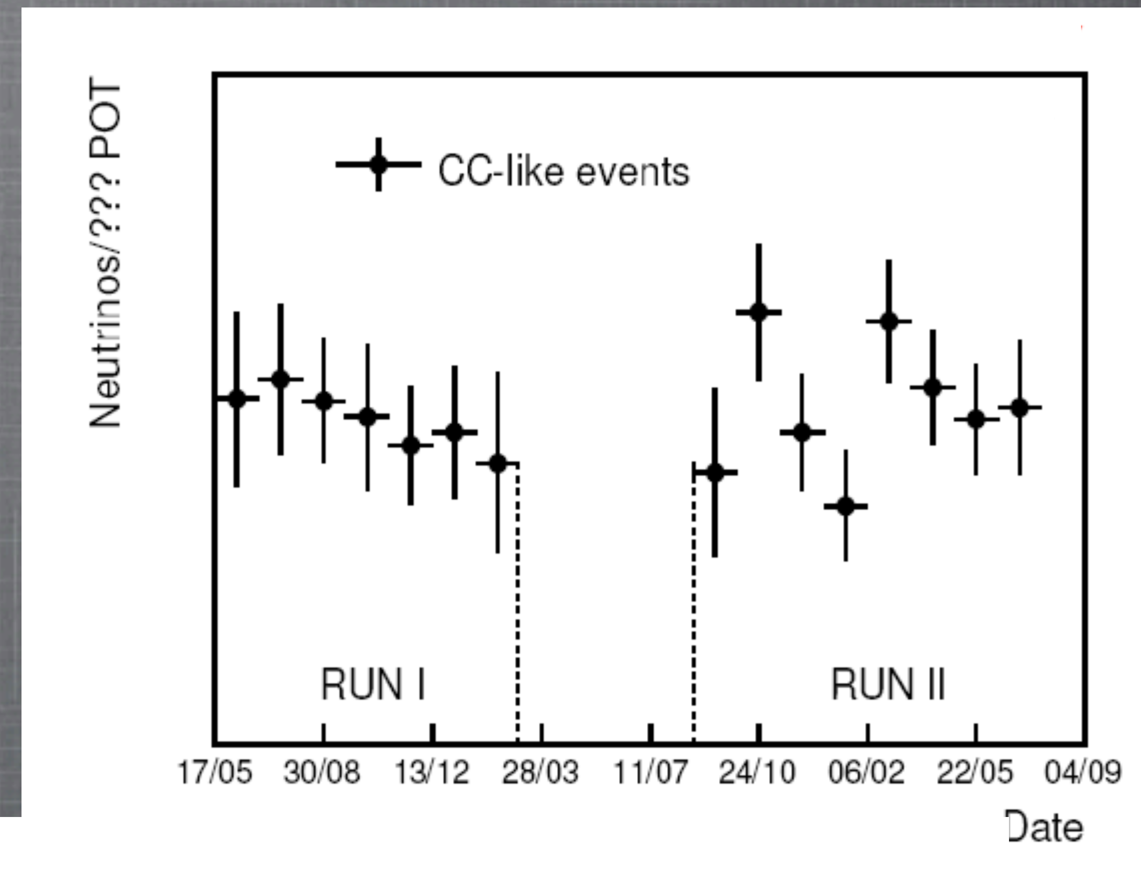


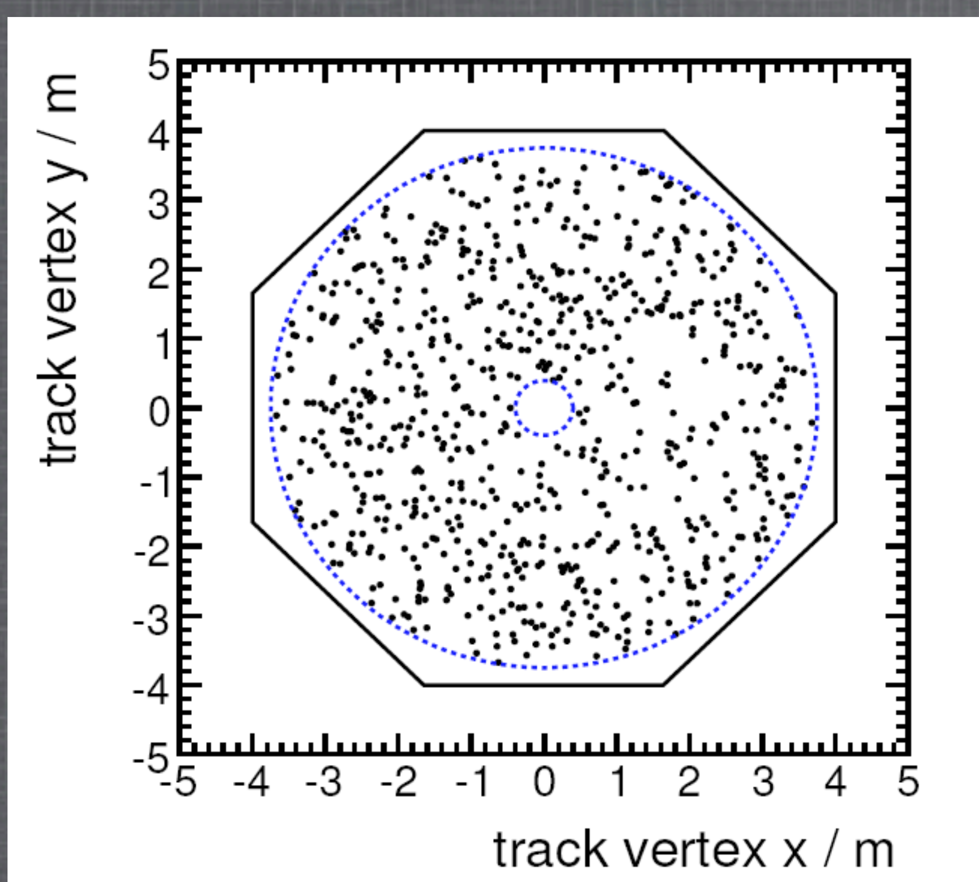


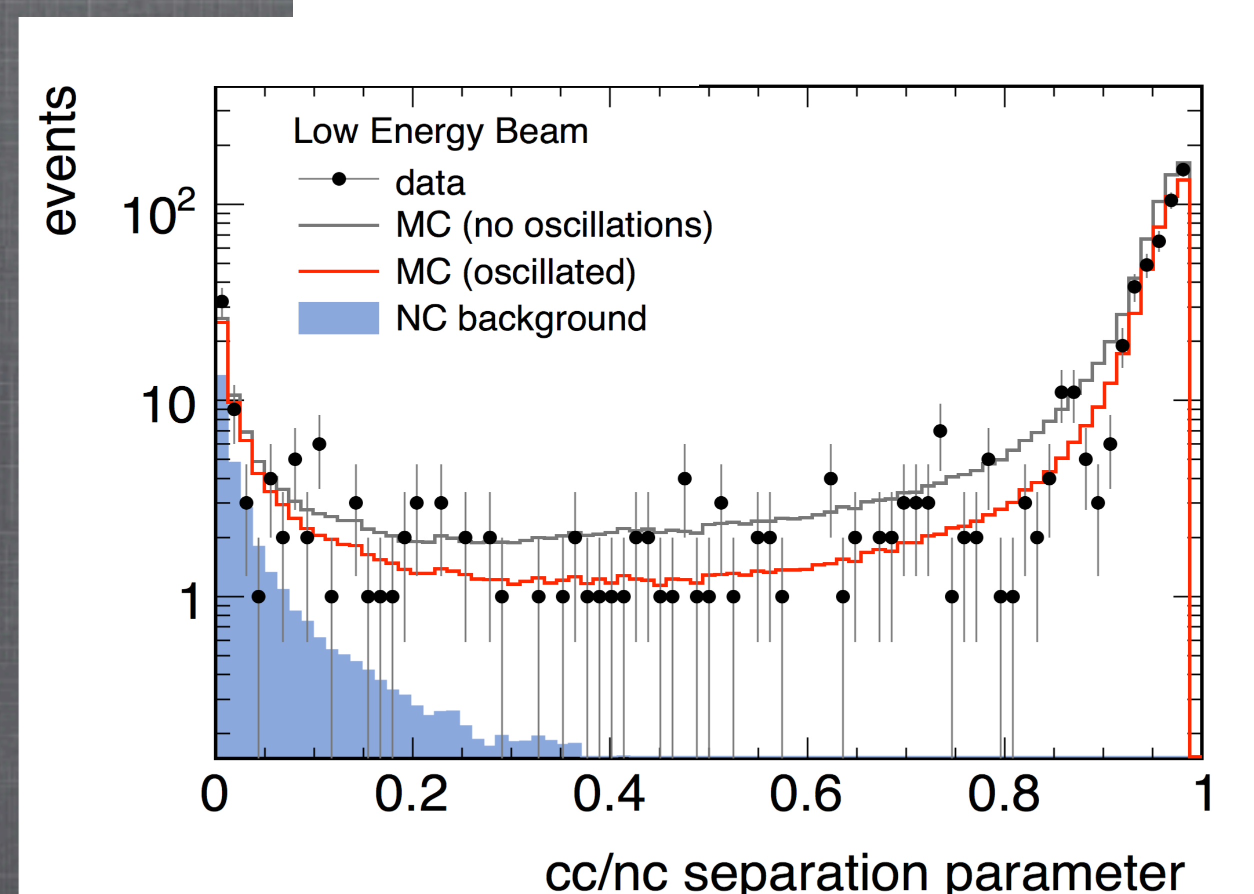
- Ckov has ~5 pe per β=1 particle.
- ToF resolution is ~300 ps
- TPC <dE/dx> resolution is ~12 %.

Far Detector Low-level Data Quality Checks

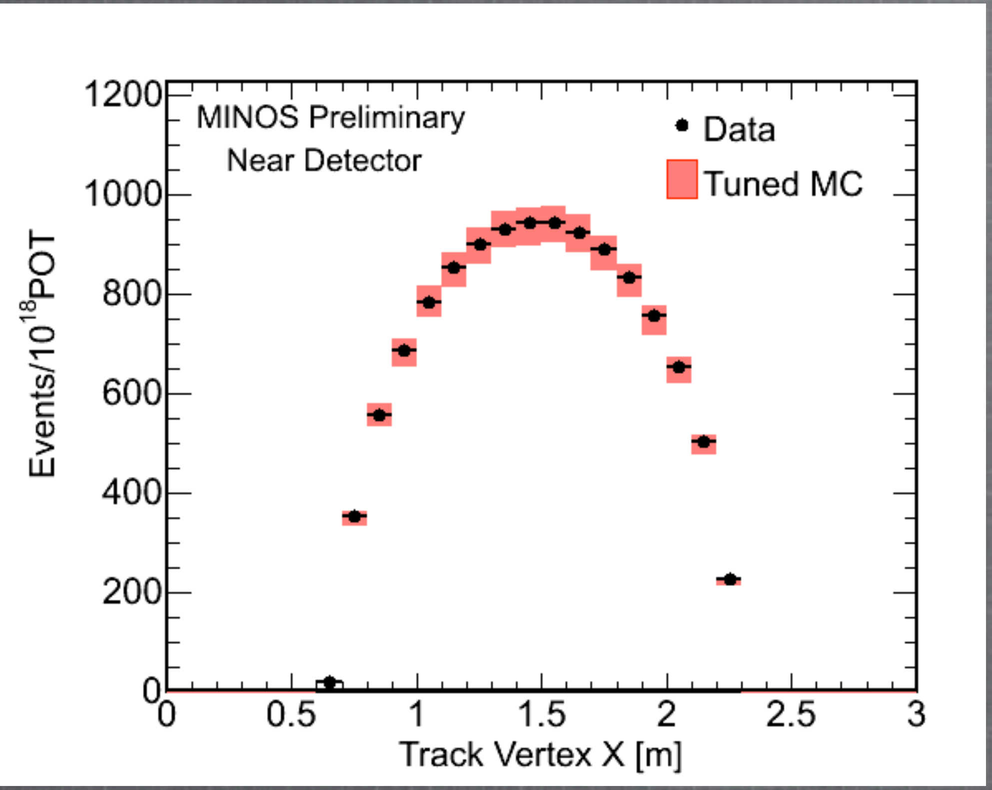
- FD energy spectrum is only looked at after performing:
  - low-level data quality checks
  - procedural checks

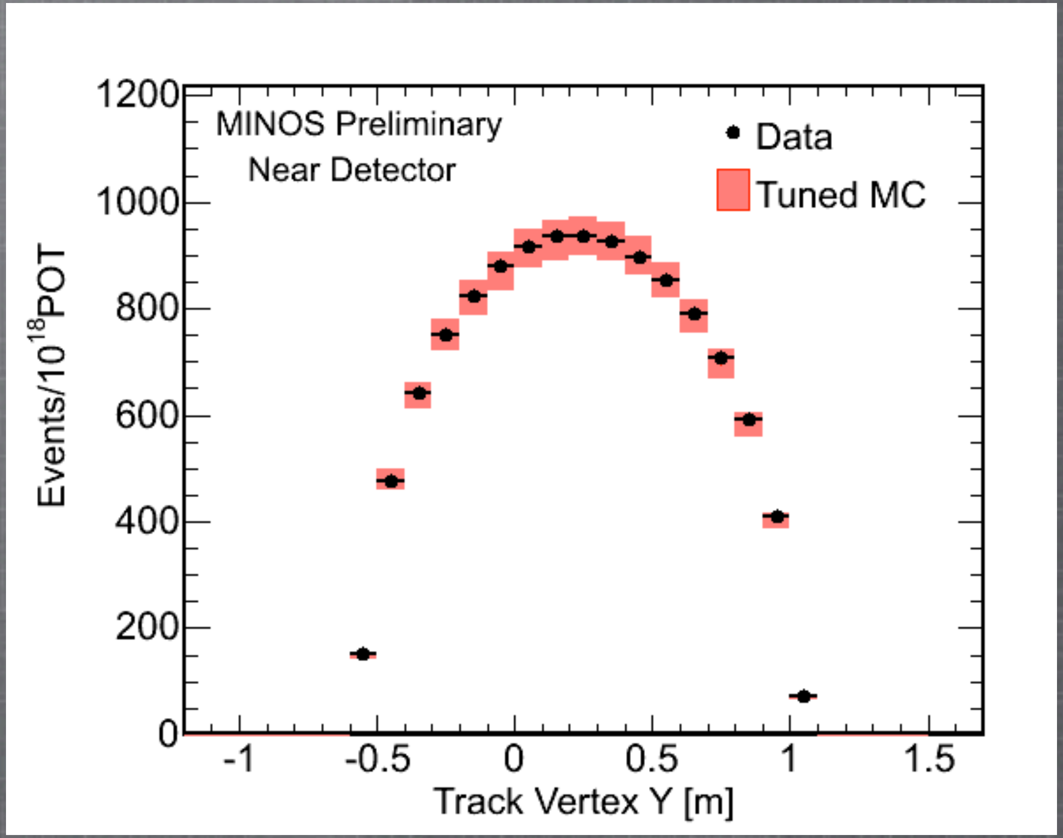


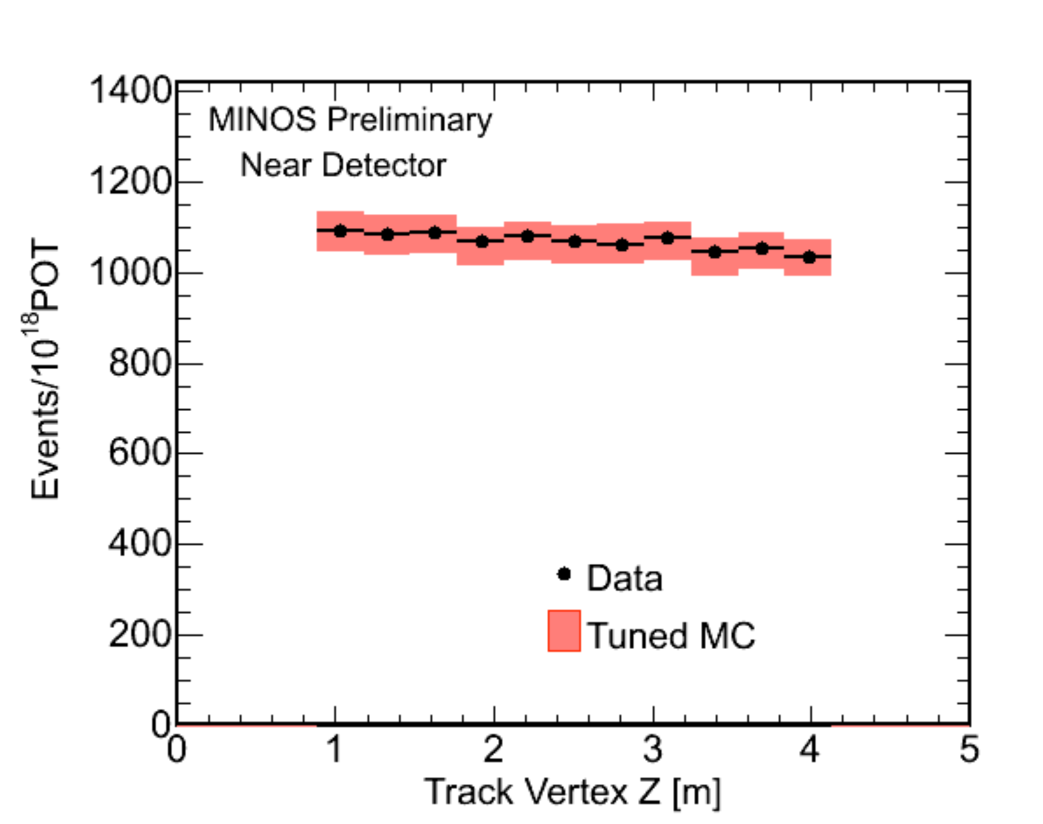




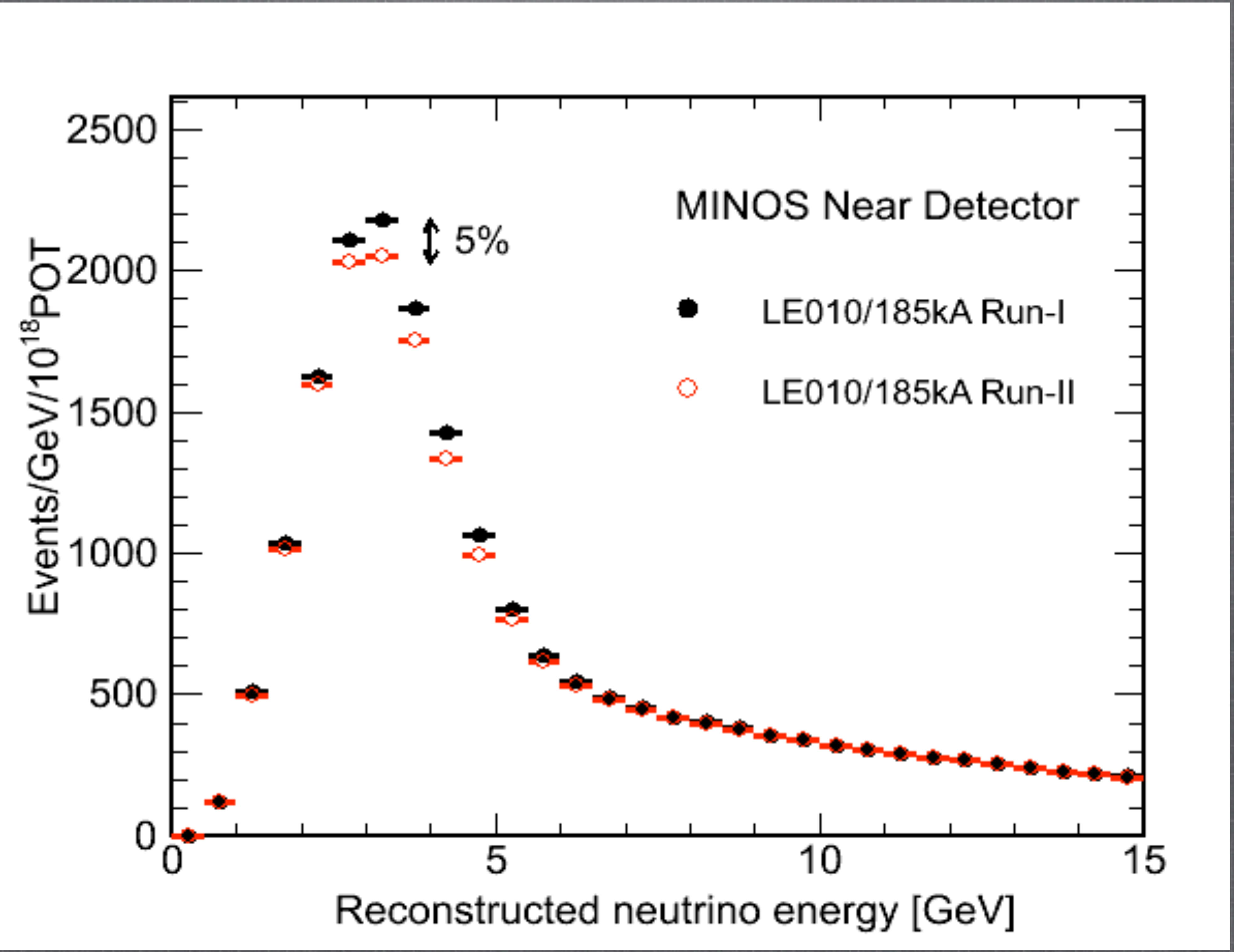
ND Distributions After Making PID Cut







LE1 vs. LE2 Beam Configurations



QUESTIONS I HAVE

- Will the NC result be redone with our latest values of dm2 and sin2(2θ)?
- Should I mention the Horn 1 problem?
- Can I mention the Nature article submission?

NOTE:

- I intend to add more backup slides, but if you have any specific suggestions, please let me know!